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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

NOVEMBER 1958

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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTICES

All-Day Discussion on Hypersonic Flow

Admission to the All-Day Discussion on Hypersonic Flow at the Institution of Mechanical Engineers on 15th December 1958 *will be by special ticket only* for members *and* non-members. Applications for tickets should be made to the Secretary and until *8th December* will be issued to members only. Thereafter any seats available will be issued to non-members in strict rotation.

The All-Day Discussion will begin at 9.45 a.m. Details are given in the Diary Section.

Associate Fellowship Examination, December 1958

The next Associate Fellowship Examination will be held on Tuesday, Wednesday and Thursday, the 16th, 17th and 18th December 1958. All candidates will be sent a detailed time-table.

Income Tax Relief

The attention of members is particularly drawn to the following:—

Copy of Letter from Chief Inspector of Taxes Branch, Inland Revenue, Dated 17th October 1958

Reference: C.I./SUB/306

Dear Sir,

I have to inform you that the Commissioners of Inland Revenue have approved The Royal Aeronautical Society for the purposes of Section 16, Finance Act, 1958, and that the whole of the annual subscription paid by a member who qualifies for relief under that Section will be allowable as a deduction from his emoluments assessable to income tax under Schedule E. If any material relevant change in the circumstances of the Society should occur in the future you are requested to notify this office.

I should be glad if you would inform your members as soon as possible of the approval of the Society. The circumstances and manner in which they may make claims to income tax relief are described in the following paragraphs, the substance of which you may care to pass on to your members.

Commencing with the year to 5th April 1959 a member who is an office holder or employee is entitled to a deduction from the amount of his emoluments assessable to income tax under Schedule E of the whole of his annual subscription to the Society *provided that*—

(*a*) the subscription is defrayed out of the emoluments of the office or employment, *and*,

(*b*) the activities of the Society so far as they are directed to all or any of the following objects—

(*i*) the advancement or spreading of knowledge (whether generally or among persons belonging to the same or similar professions or occupying the same or similar positions);

(*ii*) the maintenance or improvement of standards of conduct and competence among the members of any profession;

(*iii*) the indemnification or protection of members of any profession against claims in respect of liabilities incurred by them in the exercise of their profession;

are relevant to the office or employment, that is to say, the performance of the duties of the office or employment is directly affected by the knowledge concerned or involves the exercise of the profession concerned.

A member of the Society who is entitled to the relief should apply to his tax office as soon as possible *after 31st October 1958* for form P358 on which to make a claim for adjustment of his pay as you earn coding.

Yours faithfully,

(*signed*) T. Dunsmore,

Senior Principal Inspector of Taxes.

The Secretary,
The Royal Aeronautical Society.

Historic Aircraft Maintenance Group

An excellent response was received from members to the appeal made by the Secretary in the July Journal for volunteers to help to maintain the aircraft of the Nash Collection, which are now housed at Hendon. The Historic Aircraft Maintenance Group has now been formed jointly by the Society and the Society of Licensed Aircraft Engineers. Captain E. D. Ayre, A.F.R.Ae.S., M.S.L.A.E., a Past President of the S.L.A.E., has been appointed Chief Engineer and will supervise a team of engineers who have had extensive practical experience on the types of aircraft and engines in the Nash Collection.

The guiding principle of the Maintenance Group will be preservation rather than renovation and work has already started at Hendon.

It is hoped that ultimately the Nash Collection will form part of a National Collection of Aircraft.

Honours Awarded to Members

His Excellency Mr. John Hay Whitney, The American Ambassador, presented the following Honours to members of the Society on behalf of the President of the United States of America:

L. Boddington, C.B.E. (*Fellow*), Medal of Freedom (Co-Inventor of the Angled Deck).

Dennis Lean (*Associate Fellow*), Medal of Freedom (Co-Inventor Mirror Sight).

C. C. Mitchell, O.B.E. (*Associate Fellow*), Medal of Freedom, for his invention of the Steam Catapult.

Course on the Effect of Noise on Structures

A Course on the Effect of Noise on Structures is to be held in the Aeronautical Engineering Department of the University of Southampton from 15th to 20th December 1958. The Course is designed for people having no previous knowledge of Acoustics and will cover the subjects of Noise Generation, the Response of Structures to Random Pressure Fields, Correlation, the Damping and Fatigue of Structures and Panel Testing.

Accommodation will be available in one of the University Halls of Residence and the total course fee (including residence) will be 20 guineas. Applications should be addressed to Mr. D. J. Mead, Department of Aeronautical Engineering, The University of Southampton, **not later than 1st December 1958.**

Postgraduate Education in Aircraft Materials

A Department of Aircraft Materials has now been established at The College of Aeronautics, Cranfield, so that in the future students may elect to take this subject as their main specialisation in the postgraduate College Diploma course. This new specialisation will embrace engineering techniques in applications of materials as well as the basic relevant sciences, particularly physical metallurgy and solid state physics. It will cover both metals and non-metallic materials, and will deal especially with such subjects as high-temperature behaviour, dynamic stressing and fabrication. Research forms an essential part of the Department, and several investigations are now in progress, mainly in the fields of creep and fatigue. Students will co-operate in such researches as part of their thesis work.

In establishing this new activity within the framework of the present College Diploma, the Department can also offer Courses outside the Diploma syllabus on the mechanical, electrical or magnetic properties of materials.

A short course on materials, of about two months' duration, will be open to industry generally. The aim of such a course is to present to those concerned with engineering applications of materials a working knowledge of modern developments in materials theory and technology. Those interested should write to Professor A. J. Kennedy, The College of Aeronautics, Cranfield, Bletchley, Bucks.

DIARY

LONDON

11th November

LECTURE—Boundary Layer Control to Produce High Lift at Low Speeds. Dr. J. Williams. **The Theatre, Park Lane House, 45 Park Lane, W.1. 7 p.m. NOTE CHANGE OF VENUE.**

20th November

THE SECOND LANCHESTER MEMORIAL LECTURE—Aeroelasticity—Retrospect and Prospect. Professor A. R. Collar. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

24th November

LECTURE*—Inertia Guidance. J. E. Pateman. The Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

4th December

MAIN LECTURE AT BIRMINGHAM BRANCH—Freighters: A General Survey. E. D. Keen. College of Technology, Birmingham. 7 p.m.

9th December

LECTURE—Application of a Constant Frequency A.C. Electrical System to Aircraft and Missiles. S. S. Hall and A. Thomas. **The Theatre, Park Lane House, 45 Park Lane, W.1. 7 p.m. NOTE CHANGE OF VENUE.**

15th December

All Day Discussion on Hypersonic Flow. Introductory papers will be read by: R. J. Monaghan, Professor M. J. Lighthill, R. N. Cox, K. W. Mangler, L. F. Crabtree, Dr. D. W. Holder, J. A. Shercliff and T. R. F. Nonweiler. The Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. 9.45 a.m. **Admission will be by ticket only. See Special Notice.**

17th December

LECTURE*—Drone Aircraft. H. G. Conway. The Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.) **NOTE CHANGE OF DATE.**

18th December

MAIN LECTURE—Air Traffic Control Over the North Atlantic. E. W. Pike. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

*** Arranged by the Committee of the Guided Flight Section.**

GRADUATES' AND STUDENTS' SECTION

11th November

The Air Transport Auxiliary. Sir Gerard D'Erlanger. Library, 4 Hamilton Place. 7.30 p.m. (Coffee at 7 p.m.)

28th November

Annual Dance. Library, 4 Hamilton Place. 7.30 p.m.

9th December

The Future of the British Aircraft Industry. E. C. Bowyer. Library, 4 Hamilton Place. 7.30 p.m. (Coffee at 7 p.m.)

BRANCHES

11th November

Boscombe Down—The Application of an A.C. Electrical System to Aircraft. S. S. Hall. A. and A.E.E. Lecture Hall. 5.45 p.m.

12th November

Bristol—Joint Meeting with the I.P.E.—Some Thoughts on the American and British approach to Aircraft and Aero-Engine Procurement and Production. Air Cmdre. F. R. Banks. Filton House. 6 p.m.

Brough—The Fifth Sir George Cayley Memorial Lecture—The History of the Blackburn Company. G. E. Petty. Writing Room, Royal Station Hotel, Hull. 7 p.m.

Chester—Aircraft in Agriculture. R. E. Bird. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Hatfield—Aviation, Medicine and Air Crew Personal Equipment. Flt. Lt. J. King. de Havilland Restaurant. 6.15 p.m.

Manchester—Digital Differential Analysers. K. V. Diprose. Reynolds Hall, College of Technology. 7.30 p.m.

Reading—Film Show. Canteen, Western Manufacturing Ltd. 6.15 p.m.

Southend—Film Show. Labour Hall, Boston Ave. 7.30 p.m.

13th November

Swindon—The Fairey Rotodyne. D. M. Davies. The College, Victoria Road. 7 p.m.

17th November

Halton—Flight Refuelling. P. G. Proctor. Branch H.Q., R.A.F. Halton. 6.45 p.m.

Henlow—The Objects and Methods of Aerial Survey. J. H. Saffery. Building 62, R.A.F. Technical College. 7.30 p.m.

18th November

Bristol—Ram-jets. Dr. R. R. Jamison. Filton House. 6 p.m.

Luton—Discussion Paper Evening. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

19th November

Coventry—Successful Re-entry into the Atmosphere. W. F. Hilton. Wine Lodge, The Burges. 7.30 p.m.

Preston—Film Evening. R.A.F. Association Hall. 7.30 p.m.

Weybridge—The Training of a Production Engineer for the Aircraft Industry. Prof. J. Loxham. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

20th November

Cheltenham—Some Aspects of Design of the A.W.650 Aircraft. E. D. Keen. St. Mary's College, St. George's Place, Cheltenham. 7.30 p.m.

21st November

Brough—Annual Dinner and Dance. Jackson's Ballroom, Hull.

Luton—Annual Dinner. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

25th November

Belfast—Film Show. Sir William Whitla Hall, The Queen's University. 7.30 p.m.

26th November

Bristol—Junior Members Paper Competition. Filton House. 6 p.m.

Christchurch—Parachutes. F. B. Jackson. King's Arms Hotel. 7.30 p.m.

27th November

Isle of Wight—The Water Barrier has been Broken. P. R. Crewe. Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

Southend—Agricultural Aircraft. Labour Hall, Boston Avenue. 7.30 p.m.

1st December

Derby—Thrust Reversal for Jet Aircraft. R. H. Colley. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.

Halton—The Solar System. Sqdn. Ldr. E. A. Newman. Branch H.Q., R.A.F. Halton. 6.45 p.m.

Henlow—Long Range Forecasting. Sir G. Sutton. Building 62, R.A.F. Technical College. 7.30 p.m.

2nd December

Luton—Satellites. E. M. Dowlen. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

4th December

Bristol—Britannia: An Operator's Report. Filton House. 6 p.m.

Christchurch—Joint Lecture with the Institution of Mechanical Engineers. Aero Engines, Past, Present and Future. A. D. Baxter. King's Arms Hotel. 7.30 p.m.

London Airport—Airline Operational Flying. Capt. W. Baillie. B.E.A. Viking Centre Cinema, L.A.P. 6 p.m.

9th December

Boscombe Down—Beating the Heat Barrier. J. Taylor. Lecture Hall, A. and A.E.E. 5.45 p.m.

Bristol—Junior Committee Lecture: Nuclear Propulsion. A. D. Baxter. Filton House. 6 p.m.

Glasgow—Graduates' and Students' Section: Training the Aeronautical Engineer. A. W. Babister. Engineering Dept., University of Glasgow. 7.30 p.m.

10th December

Brough—Procedure of Test Flying at Supersonic Speeds. Wing Cmdr. R. P. Beamont. Lecture Hall, Electricity Offices, Ferensway, Hull. 7.30 p.m.

Chester—Interplanetary Instrumentation. B. P. Clear. Lecture Theatre, Grosvenor Museum. 7.30 p.m.
Christchurch—Electronic Control of Machine Tools. H. Ogden. King's Arms Hotel. 7.30 p.m.
Coventry—Junior Lecturettes and Films. Wine Lodge, The Burges. 7.30 p.m.
Gloucester—The Development of High Performance Sailplanes. D. H. G. Inge. The Wheatstone Hall, Brunswick Road. 7.30 p.m.
Manchester—Civil Aircraft Production. P. Imlach. Reynolds Hall, College of Technology. 7.30 p.m.
Preston—Emergency Stopping of Aircraft with over-run Airfield Runways. Dr. J. Thomlinson. R.A.F. Association Hall. 7.30 p.m.
Reading—Servicing of Civil Aircraft. J. Gregory. Canteen, Western Manufacturing Ltd. 6.15 p.m.
Swindon—"Any Questions." The College, Victoria Road. 7 p.m.
Weybridge—R. K. Pierson Memorial Lecture. B. S. Shenstone. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

11th December
Isle of Wight—Annual General Meeting and Film Show. Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

12th December
Belfast—Annual Dance. Midland Hotel, Belfast.

15th December
Henlow—Medical Aspects of High Speed and Space Flight. Wing Cmdr. W. A. Crawford. Building 62, R.A.F. Technical College. 7.30 p.m.

17th December
Southend—Film Show. Labour Hall, Boston Avenue. 7.30 p.m.

19th December
Weybridge—Annual Dance.

News of Members

C. G. H. Abrahams (*Graduate*) formerly with Vickers-Armstrongs (Aircraft) Ltd., Weybridge has been appointed an Experimental Officer in the Research and Development Branch of the United Kingdom Atomic Energy Authority.

Captain W. B. Axford (*Associate Fellow*), formerly with the Ministry of Supply has been appointed Chief Development Engineer at Westland Aircraft Ltd.

M. C. C. Bampton (*Graduate*), formerly Stress Engineer with the English Electric Co. Ltd., is now with Avro Aircraft Ltd., Canada, as a Thermoelastics Engineer.

V. F. Bignell (*Student*) is now at Northampton College of Advanced Technology taking a Master of Science Degree.

Squadron Leader B. J. Brooks (*Associate*), formerly Officer Commanding Armament Squadron, No. 228 O.C.V., has retired from the Royal Air Force.

P. Vince Brown (*Associate Fellow*), previously at the Ministry of Supply, St. Giles Court has been transferred to the Aircraft and Armament Experimental Establishment, Boscombe Down, Aircraft Engineering Division.

Alan A. Butler (*Student*), formerly employed as a Stressman with Bristol Aircraft Ltd., is now a Stressman with English Electric Co. Ltd., at Stevenage.

R. H. Cozens (*Associate Fellow*) has left Saunders-Roe Ltd., and is now a Senior Stress Engineer at Handley-Page (Reading) Ltd.

D. K. Craig (*Student*) has finished his engineering apprenticeship with B.E.A. and is now a Technical Assistant in the Project and Development Branch of B.E.A.

R. C. Cussons (*Associate Fellow*) is now Assistant Chief Designer with the Aviation Division of the Dunlop Rubber Co.

E. Downham (*Associate Fellow*) has resigned from the Civil Service and is now a Reader in Mechanical Engineering at the College of Technology, Birmingham.

P. W. Dryland (*Associate Fellow*), formerly Manager, Design and Development, Goodyear Tyre and Rubber Co. Ltd., is now Assistant Chief Engineer, United Kingdom Atomic Energy Authority, Chemical Plant Design Office, Risley.

A. E. Fishlock (*Associate Fellow*), formerly Principal Inspector, Ministry of Supply, Kidbrooke, is now Principal Production Officer, Ministry of Supply, St. Giles Court.

D. H. Freeston (*Graduate*), formerly Technical Engineer, Installation and Development Department, Bristol Aero Engines Ltd., is now a Lecturer at the Rugby College of Engineering Technology.

Jeffrey Green (*Student*), on obtaining his Diploma of the College of Aeronautics, Cranfield, has been appointed Technician with the Weapons Research Division of A. V. Roe and Co. Ltd., Woodford.

J. Grimson (*Graduate*), on obtaining his Diploma of the College of Aeronautics, Cranfield, has been appointed Assistant Engineer in the Wind Tunnel Department of the English Electric Co. Ltd., Warton.

R. N. Hollock (*Associate Fellow*) formerly with Vickers-Armstrongs (Aircraft) Ltd., Weybridge, is now Assistant General Manager, Scottish Aviation Ltd.

Peter M. Hughes (*Graduate*), formerly with the Aircraft Division of English Electric Co. Ltd., is now with Imperial Chemical Industries Ltd., Dyestuffs Division as an engineering management trainee.

Wing Commander R. F. Jones (*Associate*), formerly Senior Technical Officer at R.A.F. Oakington, is now serving with Headquarters Air Materiel Command, U.S.A.F., Dayton, Ohio.

M. D. Kimber (*Associate Fellow*), formerly Assistant Chief Stressman at Marshalls Flying School, is now a Senior Research Engineer at Hunting Engineering Ltd., Luton.

E. D. King (*Associate Fellow*), formerly Chief Technician at Edgar Percival Aircraft Ltd., is now with Hunting Engineering Ltd., as Research Engineer.

D. J. Ll. Lewis (*Graduate*) has taken up an appointment as an Experimental Engineer (Instruments), with British Nylon Spinners Ltd. of Pontypool.

J. C. Lewis (*Graduate*) has been appointed Lecturer at Imperial College, South Kensington.

V. Marples (*Graduate*) is now a Departmental Demonstrator in the Dept. of Engineering at Oxford University.

L. Martin (*Associate*) is now a Senior Designer with H. M. Hobson Ltd., at Wolverhampton.

H. Moon (*Associate Fellow*), formerly Assistant Chief Stressman with Gloster Aircraft Ltd., has been appointed Education and Training Officer with Ransome and Marles Bearing Co. Ltd., Newark.

Squadron Leader W. Muirhead (*Associate Fellow*) has been posted from R.A.F. Station St. Athan to R.A.F. Seletar, as Officer Commanding General Engineering Squadron at the Maintenance Base.

N. S. P. Naidu (*Associate Fellow*) has been appointed Assistant Professor, Design and Production, Madras Institute of Technology, Madras.

S. R. M. Nichols (*Associate Fellow*) is now a Senior Designer at the Lockheed Missile Systems Division at Palo Alto, California.

L. W. A. Osborne (*Associate*), formerly an Operational Officer (Engineering and Licensing) with the Department of Civil Engineering, Singapore is now Assistant Chief Inspector (Civil), Fairey Aviation Co., at White Waltham.

Ralph Parker (*Associate Fellow*), formerly with Rolls-Royce Ltd., Derby is now an Engineer in the Gas Turbine Department of the English Electric Co. Ltd., Whetstone, Leicestershire.

Air Commodore G. J. C. Paul (*Associate Fellow*) has been appointed Secretary General of the Air League of the British Empire.

Group Captain B. Robinson (*Associate Fellow*), formerly Deputy Director of Technical Services, Air Ministry, has been posted to Wright-Paterson Air Force Base, Dayton, Ohio, for duty with the U.S.A.F.

S. W. U. TUBBS (*Graduate*), formerly Design Draughtsman, de Havilland Aircraft Co. Ltd., is now Assistant Chief Engineer, Mathias Spencer and Sons Ltd., Sheffield.

Squadron Leader C. G. WEEKS (*Associate*), formerly Electrical/Instrument Officer, Headquarters, Flying Training Command, is now Mechanical Transport Officer on the Staff of Headquarters, British Forces, Aden Peninsular.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Howard Barrett
John Michael Beaumont (*from Graduate*)
Cyril Leonard Bessey (*from Associate*)
Derek Bollworthy (*from Graduate*)
George Bond (*from Associate*)
Quentin Bowker
John Brenchley (*from Graduate*)
Eric John Brice
John Reginald Bryans (*from Associate*)
Edward Christopher Carter (*from Graduate*)
Albert Leonard Cattermull (*from Associate*)
Sailendranath Roy Chaudhury
David John Childs
Richard Arthur Clarke (*from Graduate*)
Reginald Mark Diamond (*from Graduate*)
John Carlin Dickison
Ronald Edward Dudley (*from Graduate*)
Anthony Howard Endley (*from Graduate*)
Albert George Roy Ford
William Watson Gibb
Frank Herbert Gray
Roland Anthony Garth Gray (*from Graduate*)
Gerald Harrison (*from Graduate*)
Arthur Graham Hopper (*from Graduate*)
Michael Stanley Hunt (*from Graduate*)
Michael William Mark Jenkins (*from Graduate*)
Wyndham Morgan John (*from Graduate*)
Clement Wynter Lister
John Love (*from Associate*)
John Michael McDermott (*from Graduate*)
David James Masters (*from Associate*)
David Anthony Rhys Matthews (*from Graduate*)
Arthur Reynolds
David Chalmers Robertson
Jack Schofield
Paul Simpkin (*from Graduate*)
Harold David Steger-Lewis
Russell George Strachan
James Wood Thain (*ex Associate*)
Ronald Charles Turner
Maxwell Raymond Weston

Associates

Norman Leonard Angell
Samuel Francis William Aukland
Douglas Robert Stewart Bader
David Gerald Sydney Barrett
Norman Arnold Battey
Gilbert Leonard Bernard Brice (*ex Associate*)
Ronald Anderson Reid Chalmers
Leonard George Cramp
Roger Hamilton Godfrey
Francis William Huxley
Eric Pryce Jones
Basil John Lewis
Anthony Valentine May
Leslie Alexander Murray
Eric Arthur Perry (*from Companion*)
Ramachandra Ramanathan
Michael Picton Sutton
Arthur William Syme (*from Graduate*)
Edward Talbot
Alan Harry Waitt

Graduates

Anthony Russell Ashmore (*from Student*)
Gordon Ross Bamford (*from Student*)
John Anthony Beasley
Richard Marshall Berry (*from Student*)
John Gordon Carter (*from Student*)
Gerald William Joseph Clapp
Graham Charles Cook
David Gordon Creighton
Sydney Gillibrand
Adrian Neville Gray (*from Student*)
Bernard Eaton Hart
Dennis Anthony Howard (*from Student*)
Michael Battye Howard
Maxwell Alan Hundleby
Frank Ireland (*from Student*)
Ian Ronald Isaac
Eric Raymond Kendall
John Peter Little (*from Student*)
Alan Moore
Karedla Pereesam
John Leslie Sellars
Ian Slater
Dennis Ulyett
William Gordon Watson

Students

Keith Adrian Brown
Anthony John Burgess
Anthony Colby
Ian James Cromar
Roland Michael Ellis
Brian Charles Foote
Robert Randall Goode
John Gould
R. Krishnamoorthy
Nigel Wickham Lewis
Geoffrey Peel
Idris Wynn Roberts
Phillip Leonard Sansom
Brian Leonard Sherlock
Michael John Silver
Kenneth George Smith
Peter Leslie Snowden
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THE INSTITUTION OF ELECTRICAL ENGINEERS FARADAY LECTURE 1958/59

This year's Faraday Lecture, "Automation," will be given by Dr. H. A. Thomas, M.Sc., M.I.E.E., Manager of the Instrumentation and Control Section of Unilever's Engineering Department, on 26th January 1959 at the Royal Festival Hall at 6 p.m. Free tickets may be obtained from the Secretary, The Institution of Electrical Engineers, Savoy Place, W.C.2. A stamped addressed envelope must accompany requests for tickets.

The lecture will also be given in Belfast, Birmingham, Bristol, Leeds, Leicester, Liverpool, Manchester, Sheffield, Southampton and Swansea.

ACKNOWLEDGMENT

The Council wish to thank J. D. Field, Esq., for presenting a number of papers belonging to the late C. Brian Field, Esq., which contained the following documents:—

(*i*) The first certificate of airworthiness and papers covering the handing over by the R.A.F. of Hawker Tomtits G-AFTA and G-AGEF. The former information has long been lost and it is understood that the aircraft's origin was hitherto unknown. (*ii*) Technical details of S.E. 5A G-EBTK. (*iii*) A set of drawings of Martinsyde F4 (Amhurst-Villiers). (*iv*) Drawings of a modification of D.H.9 and Avro 504 for banner-towing using under-wing rollers.

They also wish to thank J. L. Brewer, Esq., of Avery-Hardoll Ltd., Tolworth, at whose suggestion the documents were given to the Society.

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VOLUME 62 NOVEMBER 1958 NUMBER 575

Some Aspects of Refrigeration in Supersonic Aircraft*

by
E. J. GABBAY, B.A., B.Sc.(Hons.), M.I.Mech.E., A.F.R.Ae.S.
(Chief Aircraft Installations Engineer, Hawker Aircraft Limited)

1. Introduction

Until recently, aircraft cooling requirements were met by direct heat transfer to free stream. Flight at high subsonic speeds brought forth a need for crew compartment refrigeration. Supersonic flight may result in an extension of this technique to a wider field, particularly the cooling of equipment and temperature-vulnerable functional materials.

This state of affairs has arisen from two major factors. Firstly, the hot boundary laye. hich surrounds the aircraft and would ultimately soak it to maximum boundary kinetic temperature. Secondly, ducted air either for the engine, equipment cooling, or crew conditioning, is received at nearly stagnation temperature. This temperature increases rapidly with Mach number and reaches its first unacceptable level, *i.e.* for crew cooling, at low altitudes in the transonic range.

The overall picture with increasing Mach number is that, added to a rising rate of internally generated heat, we have an increasing heat flux from the boundary layer, while the usual heat sink, ducted ram air, as received on board, has little or no direct cooling potential. Indeed it rapidly becomes a significant heat source. This perhaps is an over-simplified statement, but good enough to indicate the general trend.

The purpose of this paper is to review some of the basic aircraft refrigeration schemes, with particular reference to their performance in high speed flight and the power penalties implied in this form of cooling; mainly for the Mach number range from 1·5 to 2·5. There will be those systems which are already familiar, and others which have not yet been applied to aircraft duties. The aim throughout is for a simplified treatment of such systems to highlight essential thermodynamic and performance aspects. To aid appreciation of the main points, basic concepts are reviewed briefly.

2. Preliminary Considerations

Refrigeration cooling is a way of inducing heat transfer from a cold body to relatively hotter surroundings or medium, thereby artificially counteracting the normal direction of heat flow. This process is, in some respects, similar to that of pumping a fluid against gravity to a higher level, and like it, requires expenditure of energy. The heat pump, however, in its particular use as a refrigerator, involves application of thermodynamic principles. It has all the essential features of a heat engine but operates in a reversed sense.

Apart from the outward manifestation of overall heat transfer from a cold source to a hot sink, the inner process of refrigeration is related to the working fluid in the machine. This has to undergo repeated cyclic changes in its thermal state. If the changes which take place in a cycle are reversible, in the thermodynamic sense, we secure the ideal or most efficient refrigeration possible, but if irreversible we incur a loss of performance by comparison to the ideal.

3. Refrigeration Cycles

3.1. BASIC THERMODYNAMIC CYCLES

For our purpose, the main cycles of interest are (*i*) the Carnot cycle, with isothermal heat transfer (ideal, reversible), and (*ii*) the Joule cycle with heat transfer at constant pressure.

Figure 1 gives representations of these cycles on a temperature entropy diagram for a gas as the working substance.

These consist of a closed sequence of operations, so that net work (W) is absorbed, heat ($H+W/J$) is rejected to a sink at the higher temperature, and finally, heat (H) is taken from the cooled medium at the lower temperature.

The ratio of heat extracted to cycle work, (JH/W) in consistent units is the coefficient of performance (c.o.p.).

For the reversible Carnot cycle working between temperatures T_1, T_2,

$$\text{c.o.p.} = \frac{T_1}{T_2 - T_1}.$$

For the Joule cycle it can be shown that,

$$\text{c.o.p.} = \frac{T_0}{T - T_0}.$$

In practice this is smaller than the value for the ideal Carnot cycle as the hot sink temperature T' is less than T.

Based on a Section Lecture given before the Society on 26th November 1957. Revised 31st January 1958.

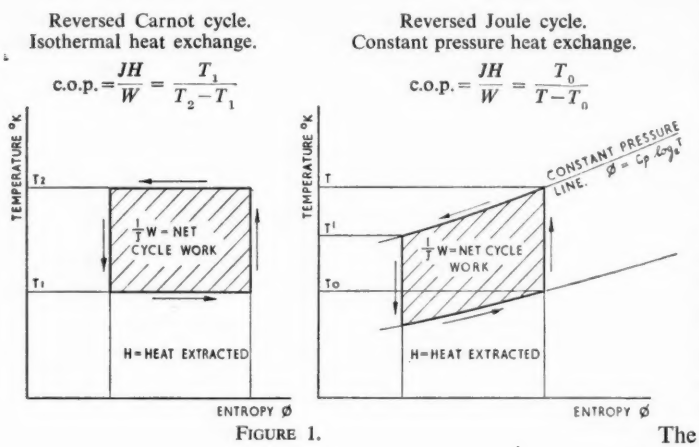


FIGURE 1.

3.2. OPEN CYCLES

The continuous air flow refrigeration systems on current aircraft approximate to the Joule cycle, but the final process where the substance reverts to its initial state often takes place after discharge to free stream.

If an open Joule cycle is operated directly from a ram scoop, down to free stream static temperature, then assuming isentropic compression and expansion, the coefficient of performance is given by,

$$\text{c.o.p.} = \frac{T_0}{T_1 - T_0} = \frac{5}{M_0^2}$$

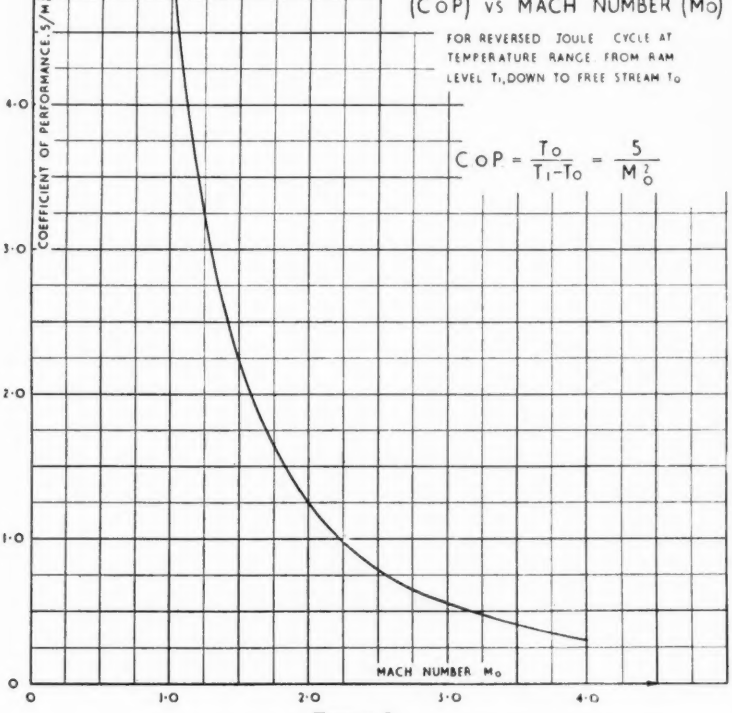


FIGURE 2.

where T_1, T_0, are ram total and free stream static temperatures respectively. M_0 is the flight Mach number.

A plot of this coefficient against Mach number is shown in Fig. 2. It is seen that it falls off steeply, reaching one at a Mach number of 2·2.

A physical representation equivalent to this cycle and the corresponding temperature entropy diagram are shown in Fig. 3. Starting from free stream conditions, temperature T_0, pressure P_0, and velocity V_0, we have first the isentropic compression in the duct to T_1. In this process work is put into the air by the aircraft propulsion unit, which appears as momentum drag power.

The refrigeration cycle proper starts at T_1 where the first stage is constant pressure cooling to T_2 in a heat exchanger, possibly a fuel cooler. This is followed by isentropic expansion in a turbine down to T_3 which is below the free stream temperature. During this stage substantial work is given up by the turbine which must be transferred to an auxiliary power absorber.

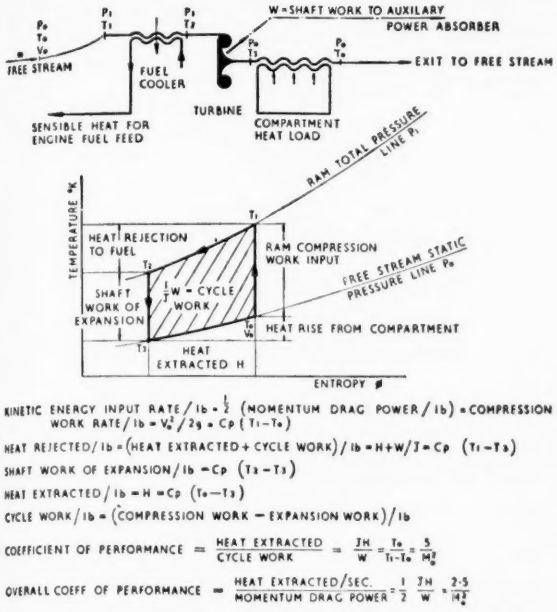
From T_3 back to T_0 we have the final phase of heat extraction at constant pressure P_0 from the low temperature body.

The power given up by the turbine is, in this scheme, ancillary to the main process. With this cycle, when the working substance (*i.e.* air) reverts to T_0, it does so at nominally zero kinetic energy.

With these ideal processes, the net cycle work is equal to the kinetic energy of the entering stream less the useful work available for the power absorber. The kinetic energy, which is totally expended, is obtained in this case at 50 per cent efficiency, that is, when considered in relation to the momentum drag power it gives rise to. Various other statements for this scheme are summarised in Fig. 3.

A point to note is that if the power absorber is not an essential item of aircraft services* but is there merely to load the turbine, then its power absorption re-appears elsewhere as heat; and although local compartment refrigeration is secured, the overall result for the aircraft is net addition of heat. This at high Mach numbers would be considerable. Also in this instance the coefficient of performance is depressed, and the weight drag power of the power absorber (*i.e.* the additional induced drag power due to the weight of the unit) must be considered as extra

*That is, a unit whose waste heat rejection within the aircraft is unavoidable.



KINETIC ENERGY INPUT RATE / lb = $\frac{1}{2}$ (MOMENTUM DRAG POWER / lb) = COMPRESSION WORK RATE / lb = $V_o^2 / 2g = Cp\,(T_1 - T_o)$

HEAT REJECTED / lb = (HEAT EXTRACTED + CYCLE WORK) / lb = $H + W/J = Cp\,(T_1 - T_3)$

SHAFT WORK OF EXPANSION / lb = $Cp\,(T_2 - T_3)$

HEAT EXTRACTED / lb = $H = Cp\,(T_o - T_3)$

CYCLE WORK / lb = (COMPRESSION WORK − EXPANSION WORK) / lb

COEFFICIENT OF PERFORMANCE = $\frac{\text{HEAT EXTRACTED}}{\text{CYCLE WORK}} = \frac{JH}{W} = \frac{T_o}{T_1 - T_o} = \frac{5}{M_o^2}$

OVERALL COEFF OF PERFORMANCE = $\frac{\text{HEAT EXTRACTED/SEC.}}{\text{MOMENTUM DRAG POWER}} = \frac{1}{2}\,\frac{JH}{W} = \frac{2{\cdot}5}{M_o^2}$

FIGURE 3. Open variant of reversed Joule cycle, work diagram.

charge to local refrigeration. The redisposal of substantial shaft power output is characteristic of open cycle aircraft systems. One method is to reject it to an auxiliary propulsive duct as shown in Fig. 4. This is by way of an engine coupled to the refrigerator proper, redisposing surplus energy into useful thrust power.

In such schemes, when account is taken of component efficiencies including duct losses, the coefficient of performance falls off steeply with rise in Mach number. Also at a given Mach number, it is mostly well below that of the ideal Joule cycle.

4. Practical Aircraft Open Cycles

4.1. CREW-COOLING

Some typical open cycles utilising air, both as the working substance and the final coolant, in a continuous flow system, are shown in Fig. 5; and comprise:—

(*i*) a completely self-contained regenerative system.

(*ii*) a bootstrap system with fuel cooling.

(*iii*) a simple cycle with an auxiliary braking compressor and fuel pre-cooling.

The performance of these systems has been assessed taking practical compressor and turbine efficiencies applicable to radial flow units, but idealising the cycles to the extent of neglecting imponderables such as system pressure drops, and assuming the initial compression to be derived entirely from intake ram corrected for shock and subsonic losses. This procedure was a necessary rationalisation to provide a common basis for comparison. The results of the analysis are given in a plot over the range of Mach numbers in Figs. 6 and 7.

(The method of analysis and assumptions, as applied to the regenerative system, are set out in Appendix I).

Before discussing the results of this working the particular cycles and reasons for their choice will be considered briefly.

First the regenerative, when the outside air is the only permitted heat sink the upper cycle temperature cannot be less than ram. In this case the regenerative cycle seems to be the most promising scheme. It really consists of a refrigerator and heat engine working in tandem. It may be run either with, or without, a precooler according to the required cooling level. Its functional disadvantages are (*i*) the necessary disposition of the heat load between the turbine and the compressor causing stray leakages to have a marked influence on performance, (*ii*) the relatively bulky heat exchanger necessary for a 1:1 mass flow ratio, and (*iii*) complications of component matching and pressure control.

The bootstrap system is purely a refrigerator and has the merit of providing its rated cooling over a wide range of flight conditions, but in practice when operated from ram input it must have a lower datum sink for

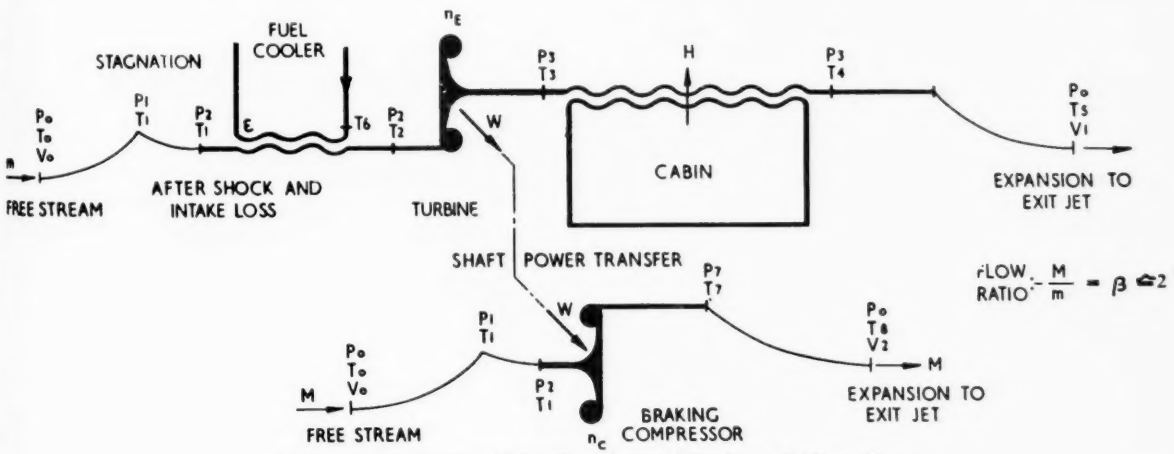


FIGURE 4. Simple open "air" cycle with propulsive duct. Cabin cooling.

its heat exchangers; *i.e.* either fuel or water evaporative cooling. Functionally, it is the simplest in respect of component matching and control for pressurised compartments. Fig. 5(*a*) gives thermodynamic comparison between a bootstrap refrigerator and a turbo-jet engine under ideal static working.

The simple cycle with auxiliary braking compressor is another example of the combined refrigerator-cum-heat engine. In this instance the two are run in parallel. Like the bootstrap, it requires a sub-ram heat sink level.

4.1.1. *Coefficients of Performance*

Figure 6 compares the coefficient of performance over the Mach number range for a constant refrigeration input of +5°C and a load rise of 30°C appropriate to minimum crew compartment cooling. Curves are given for the regenerative system from $M_0=1$ to $M_0=1{\cdot}75$ at sea level, and a set for all three systems from $M_0=1{\cdot}5$ to $M_0=2{\cdot}5$-3 at the tropopause. The uppermost curves "A" are for the loss-free Joule cycle performance.

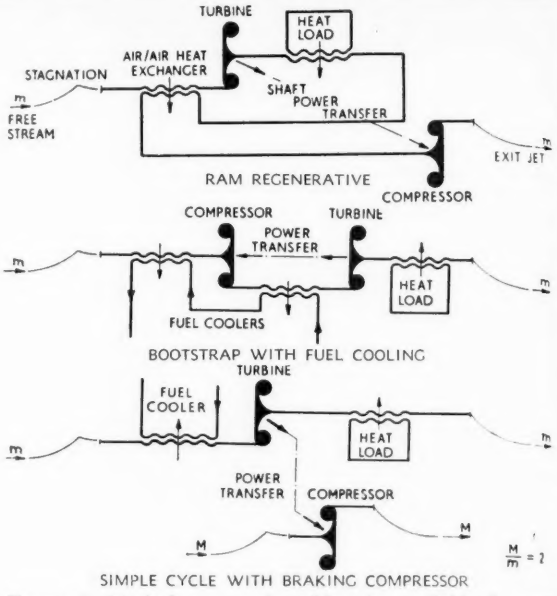
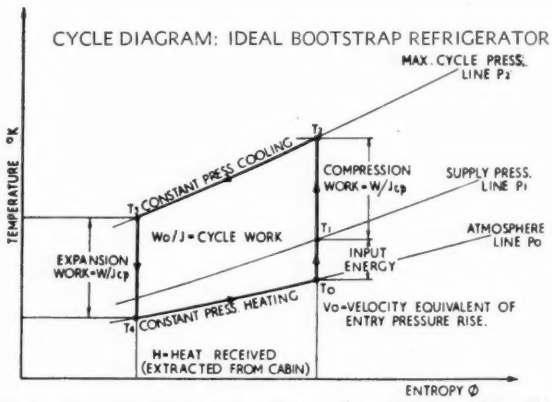


FIGURE 5. Typical open cycle refrigerators suitable for crew compartment cooling.


CYCLE DIAGRAM: IDEAL BOOTSTRAP REFRIGERATOR
MAX. CYCLE PRESS. LINE P2
TEMPERATURE °K
CONSTANT PRESS COOLING
COMPRESSION WORK = W/Jcp
SUPPLY PRESS. LINE P1
Wo/J = CYCLE WORK
ATMOSPHERE LINE Po
EXPANSION WORK = W/Jcp
INPUT ENERGY
CONSTANT PRESS HEATING
Vo = VELOCITY EQUIVALENT OF ENTRY PRESSURE RISE.
H = HEAT RECEIVED (EXTRACTED FROM CABIN)
ENTROPY Ø

Work of compression = work of expansion $= W/J = cp\ (T_2 - T_1) = cp\ (T_3 - T_4)$.

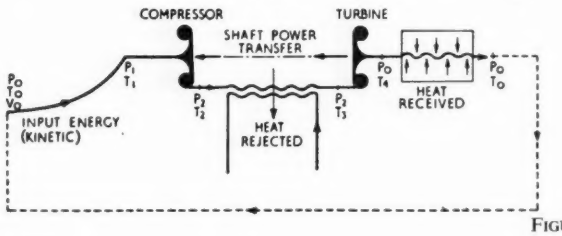
Input energy $= cp\ (T_1 - T_0) = \dfrac{1}{2Jg} V_0^2$

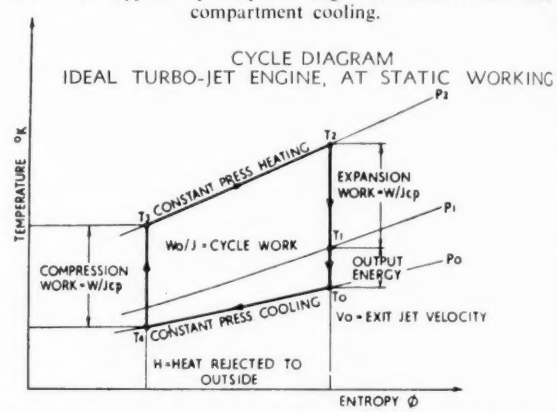
Cycle work $= W_0/J = cp\ \{(T_2 - T_3) - (T_0 - T_4)\} = cp\ (T_1 - T_0) = \dfrac{1}{2Jg} V_0^2$

Heat received $= H = cp\ (T_0 - T_4)$

Heat rejected = heat received + cycle work $= H + W_0/J = cp\ (T_2 - T_3)$

Coefficient of performance, c.o.p. $= \dfrac{\text{Heat extracted}}{\text{Cycle work input}} = \dfrac{H}{(W_0/J)} = \dfrac{T_0 - T_4}{T_1 - T_0} = 2Jg\left(\dfrac{T_0 - T_4}{V_0^2}\right)$





Work of compression = work of expansion $= W/J = cp\ (T_2 - T_1) = cp\ (T_3 - T_4)$.

Output energy $= cp\ (T_1 - T_0) = \dfrac{1}{2Jg} V_0^2$

Cycle work $= W_0/J = cp\ \{(T_2 - T_3) - (T_0 - T_4)\} = cp\ (T_1 - T_0) = V_0^2/2Jg$

Heat rejected $= H = cp\ (T_0 - T_4)$

Heat received = heat rejected + cycle work $= H + W_0/J = cp\ (T_2 - T_3)$

Thermal efficiency $= \eta_{TH} = \dfrac{\text{Cycle work output}}{\text{Total heat received}} = \dfrac{W_0/J}{H + W_0/J} = \dfrac{1}{1 + \dfrac{T_0 - T_4}{T_1 - T_0}} = \dfrac{1}{1 + 2Jg\left(\dfrac{T_0 - T_4}{V_0^2}\right)}$

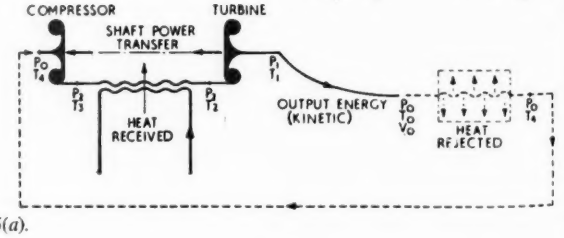


FIGURE 5(*a*).

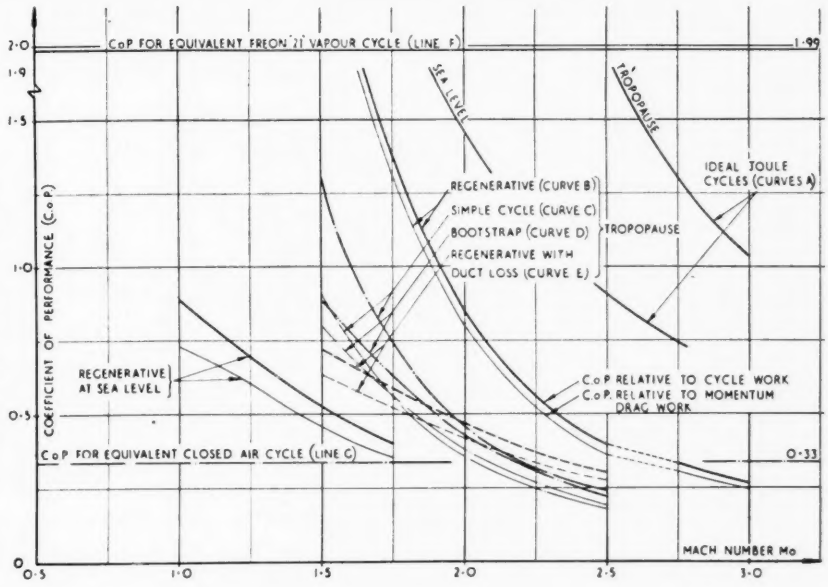


FIGURE 6. Cycle efficiencies plotted against Mach number for crew cooling. Cabin entry air temperature: 278°K. Cabin rise: 30°C.

Curves "E" are a re-working of the regenerative system with nominal heat exchange or ducting pressure drops of one and 1·5 p.s.i. respectively. As can be seen, the effect on the coefficient of performance is very pronounced. The parallel datum lines are, first "F" for a Freon 21 vapour cycle, and "G" for a closed air cycle, calculated on the basis of practical component efficiencies.*

A significant feature is that all open cycles appear to suffer a pronounced fall in performance either with rising Mach number or when the ambient temperature is high. In each case, the upper of the twin curves defines c.o.p. with respect to gross cycle work, while the lower one is relative to net momentum drag power, assuming isentropic expansion to free stream of all surplus energy.

4.1.2. *Drag and Power Loss*

An assessment of drag and power loss specifically for the regenerative system, is shown in Fig. 7. The ordinate measure is in horse power per lb./sec. of air inducted.

The base line "A" gives the constant heat load which for the assumed crew compartment temperature rise of 30°C is rated at 18·3 h.p./lb./sec.

The minimum momentum drag power to sustain this cooling load varies with Mach number and is represented by curves "B" rising to 50 h.p./lb./sec. at $M_0 = 2{\cdot}5$ at the tropopause, which is roughly the same for sea level $M_0 = 1{\cdot}75$. At these conditions the turbine shaft provides around 60 h.p./lb./sec. which must be re-absorbed. (Curves "C").

Curves "D" give the maximum available kinetic power at exit; about 120 h.p./lb./sec. at $M_0 = 2{\cdot}5$ tropopause.

In practical systems the surplus energy would be much smaller on account of ducting, heat exchange, and control losses. If this surplus energy is completely dissipated in internal ducts, or used up for purposes other than rearward ejection, then the momentum drag power would rise to the maximum value represented by curve "F," about 330 h.p./lb./sec. This is twice the kinetic energy input rate for curves "E."

The vertical measure between curves "D" and "E" is the minimum kinetic energy loss, which has been taken to represent the gross cycle work.

This outline of the specific power penalty, apart from variations in detail, is more or less characteristic of all practical open cycles, particularly at the higher Mach

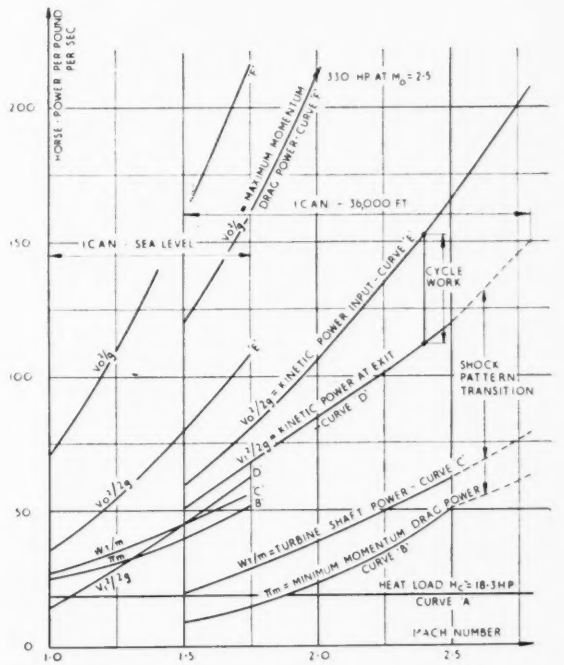
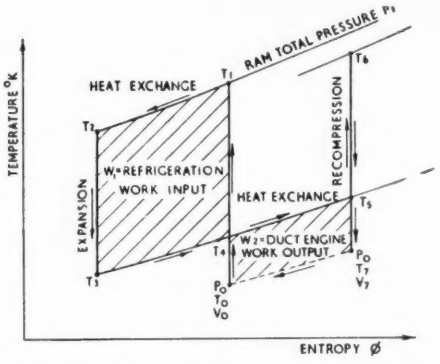


FIGURE 7. Ram regenerative refrigeration cycle performance.
Compressor: Polytropic efficiency: 71%
Turbine: Polytropic efficiency: 78%
Intake total head efficiency varies with Mach number. Allowance for intake total head efficiency, but not for internal duct losses.

*Computations for these cycles are set out in Appendices II and III. Their performance is rendered independent of Mach number and at some advantage by fuel cooling.



WORK DIAGRAM FOR IDEAL REGENERATIVE CYCLE.

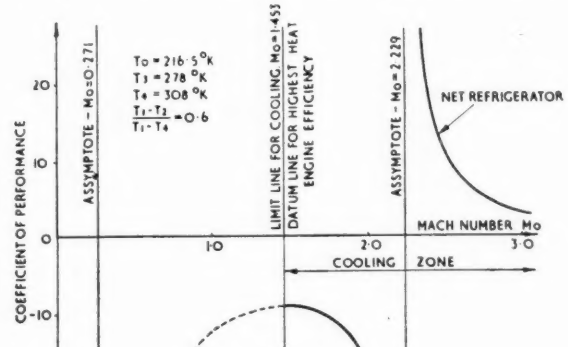
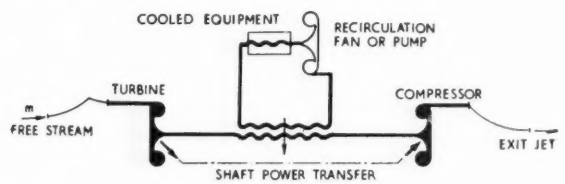
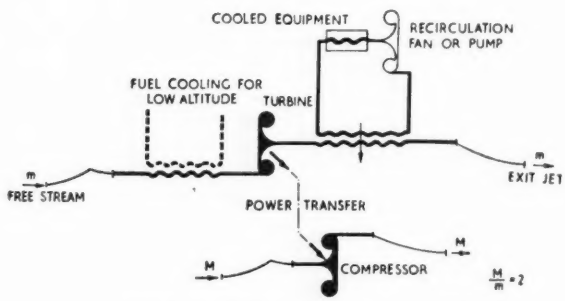


FIGURE 8. Coefficient of performance plotted against Mach number for ideal regenerative cycle.



REVERSE FLOW BOOTSTRAP
SCHEME 1



SIMPLE CYCLE WITH BRAKING COMPRESSOR
SCHEME 2

FIGURE 9. Equipment cooling.

numbers, where coefficients of performance inevitably tend to converge to low values.

Viewed with reference to momentum drag power, we may say that at $M_0=2{\cdot}5$, each h.p. of refrigeration from ram would cost at least 2·7 h.p. and at most 18 h.p. The upper limit represents a very high power expenditure by comparison with closed vapour or air cycles.

In the composite cycles considered, the coefficients of performance are computed with respect to overall cycle work. This includes auxiliary losses in intakes and the power absorber, which are rather aside to the main process of refrigeration. These losses have to be included in any assessment of power penalty, but they make comparison with an ideal Joule cycle somewhat unfavourable.

Yet another aspect of composite cycles like the regenerative is the theoretical transition to a net heat engine. When the cycle is idealised by taking 100 per cent efficiencies for the intake and components, then, with the previously assumed heat extraction rate, working at the tropopause, the cycle transforms to a net heat engine, delivering thrust power at, and below, $M_0=2{\cdot}2$. This is illustrated in Fig. 8 where the c.o.p. becomes infinite at $M_0=2{\cdot}2$ and settles to negative values below $M_0=2{\cdot}2$ down to $M_0=1{\cdot}45$ when the sense of heat flow reverses.

In practice a positive steeply rising c.o.p. is obtained in this range on account of losses. However, in the strict thermodynamic sense, the conditions of cooling below $M_0=2{\cdot}2$ for the case considered cannot be termed refrigeration.

All these results relate to a range of refrigerators, each working at the optimum design point for the associated Mach number.

4.2. EQUIPMENT REFRIGERATION

For equipment cooling it is usually permissible to operate at somewhat higher temperatures, therefore, refrigeration where required would be at moderate level, say $+60°C$ at equipment exit. With this in view two simplified variants of previously considered schemes have been chosen for comparison and sketched in Fig. 9.

Scheme 1, which in respect of disposition of heat load is similar to the regenerative cycle, is basically an engine and not a refrigerator when used for cooling to a level below stagnation but above free stream temperature. Its efficiency as an engine is, of course, very low, so that in most cases its thrust power output is swamped by intake and component losses resulting in a positive c.o.p.

Scheme 2 is a repeat of the simple cycle with braking compressor but for all calculations relating to the tropopause working it was found possible to dispense with the fuel pre-cooler.

Since in many equipment cooling applications pressurisation may be necessary to improve heat transfer, the schemes provide for waste heat rejection by transfer to an exchanger. However, apart from assuming a practical exchange thermal ratio no account is taken of pumping losses in the equipment circuit.

4.2.1. *Coefficient of Performance*

Figure 10 gives c.o.p. for equipment cooling by means of schemes 1 and 2. For strict comparison the cooling load has again been fixed at 18·3 h.p./lb./sec. corresponding to a temperature rise of 30°C. However, whereas for crew cooling the main stream picks up heat directly, for equipment, allowance is made for temperature gradient across a heat exchanger, appropriate to a thermal ratio of 0·8 as a heater. This implies a high rate of coolant circulation within the equipment and, correspondingly, a small temperature rise to exit level of 333°K.

As would be expected, in tropopause working, the c.o.p. for scheme 1, (the reverse flow bootstrap) increases rapidly below $M=2$ becoming asymptotic to $M_0=1{\cdot}43$. At this condition, the equipment could just about be cooled directly by ram air. However, because of the temperature gradient across the exchanger there exists an artificial demand for refrigeration, which persists down to $M_0=1{\cdot}36$.

In the narrow range $M_0=1{\cdot}43$ to $M_0=1{\cdot}36$, intake and component inefficiencies are overcome and the system then delivers positive thrust power. That is, the c.o.p. becomes negative even at practical efficiency values. The complete transition and the $T-\phi$ diagram for the cycle are shown in Fig. 11. For the sea level case the c.o.p. is obviously much smaller. By contrast, scheme 2 yields low c.o.p.'s throughout the Mach number range on account of scaled up intake losses. Corresponding c.o.p.'s for the closed air cycle, and the vapour cycle using Freon 21, when fuel-cooled are indicated at 0·56 and 5·3 respectively.

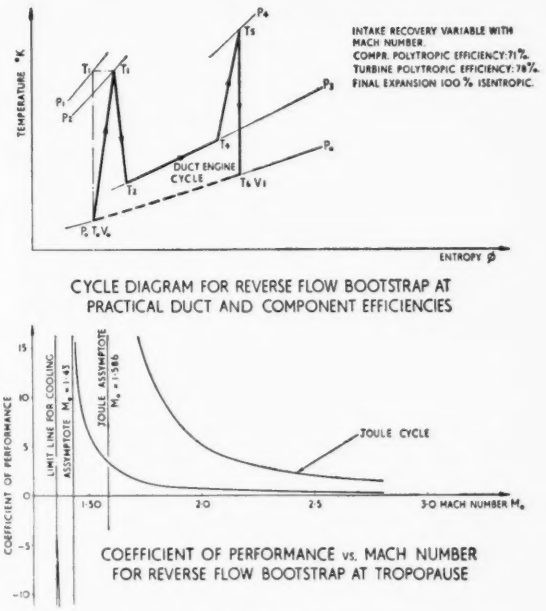

TEMPERATURE °K
ENTROPY φ
DUCT ENGINE CYCLE
INTAKE RECOVERY VARIABLE WITH MACH NUMBER.
COMPR. POLYTROPIC EFFICIENCY: 71%.
TURBINE POLYTROPIC EFFICIENCY: 78%.
FINAL EXPANSION 100 % ISENTROPIC.
CYCLE DIAGRAM FOR REVERSE FLOW BOOTSTRAP AT PRACTICAL DUCT AND COMPONENT EFFICIENCIES
COEFFICIENT OF PERFORMANCE
LIMIT LINE FOR COOLING
ASSYMPTOTE M_0 = 1·43
JOULE ASSYMPTOTE M_0 = 1·586
JOULE CYCLE
1·50
2·0
2·5
3·0 MACH NUMBER M_0
COEFFICIENT OF PERFORMANCE vs. MACH NUMBER FOR REVERSE FLOW BOOTSTRAP AT TROPOPAUSE

FIGURE 11.

4.2.2. *Drag Power*

The calculated results for the reverse flow bootstrap are shown in Fig. 12. These follow much the same pattern as the regenerative system of Fig. 7 but, due to higher turbine shaft power (absence of heat exchanger), the losses are scaled up, with the result that net

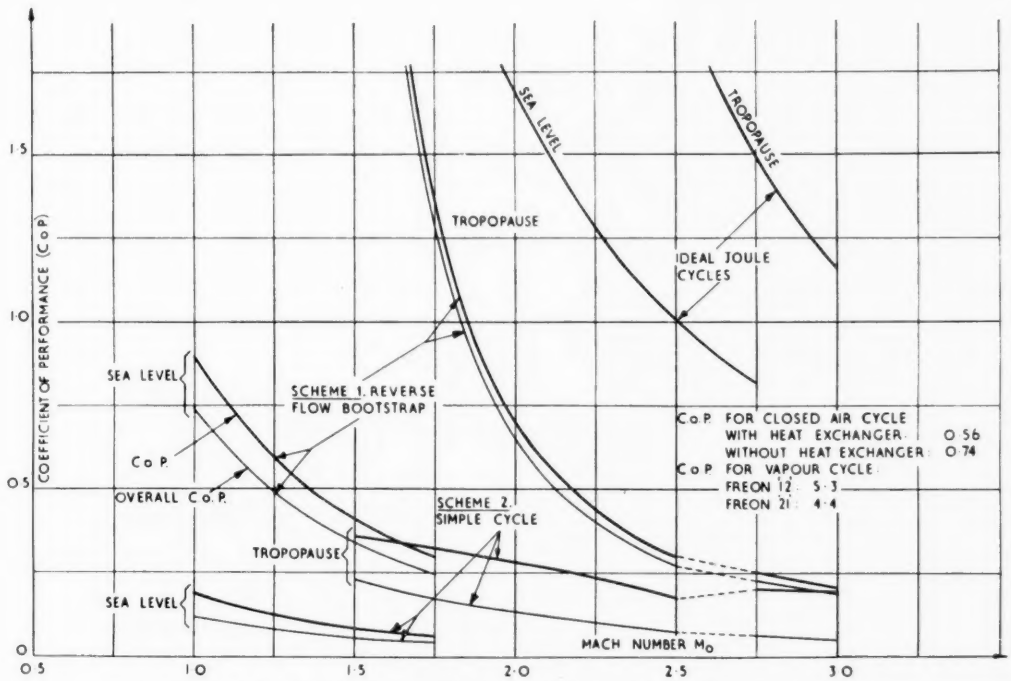


FIGURE 10. Cycle efficiencies plotted against Mach number for equipment cooling. Equipment exit temperature: 333°K. Exchanger thermal ratio: 0·8.

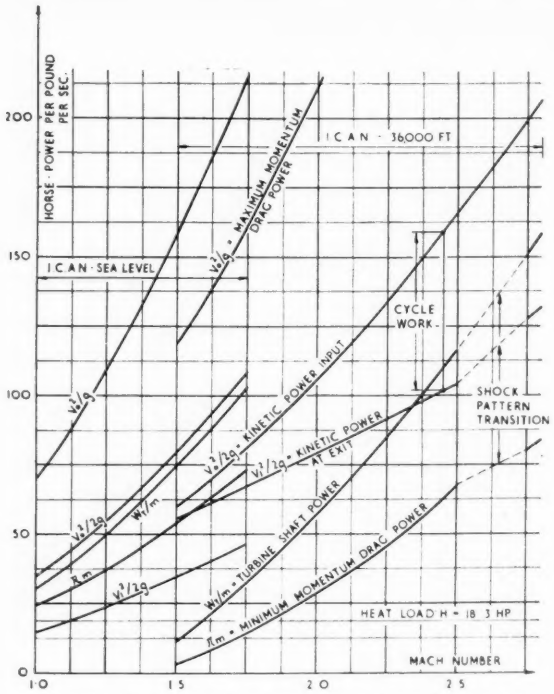


FIGURE 12. Reverse flow bootstrap cycle performance.
Equipment cooling.
Compressor: Polytropic efficiency: 71%
Turbine: Polytropic efficiency: 78%
Intake total head efficiency varies with Mach number. Allowance for intake total head efficiency, but not for internal duct losses.

momentum drag power is greater than for the regenerative system. Indeed it appears that constant pressure (loss free) heat interchange would have had a beneficial effect, but the inclusion of a heat exchanger would revert the scheme to a basic regenerative system. However, the overall effect is more likely to be a net loss, by virtue of the low level of heat transfer relative to likely pressure drops in the exchanger, and the weight drag of the unit.

4.3. OPEN CYCLES—FUNCTIONAL CONSIDERATIONS

So far, when dealing with open cycle refrigeration we have simplified by taking ram air feed and ignored essential functional aspects, to provide a common basis for comparison.

In the detail implementation of most systems, as for example crew-cooling duty, we have to ensure adequate reserve of energy to cater for (*i*) compartment pressurising spill flow, (*ii*) duct, components, and heat interchange pressure losses, (*iii*) maintenance of satisfactory cooling level at reduced aircraft speeds when ram energy is low.

To meet these requirements it has previously been found necessary to take the air supply from an engine tapping and pre-cool it by ducted ram air. With this procedure we incur additional penalties of (*a*) precooling drag power, and (*b*) net power loss of engine compressor stage (*i.e.* unavailable energy of compression). These, added to ducting and spill losses, reduce the overall efficiency of the combined refrigeration-cum-pressurisation process to a small value even at moderate Mach numbers.

Utilisation of cabin discharge air for a limited range of equipment cooling is sometimes possible and this helps to moderate the power penalty. In general, however, the open cycle process, comprising a multiplicity of thermal transformations with substantial surplus energy appearing as shaft work for redisposal, is wasteful at all stages.

A breakdown of the major losses of the regenerative cycle is now given.

A. Aerodynamic
- (*i*) Entropy increase through shock wave system at intake entry.
- (*ii*) Subsonic loss in intake duct.

B. Engine and Feed System
- (*i*) Entropy increase through engine compressor.
- (*ii*) Pressure loss through feed ductings to heat exchanger charge side.

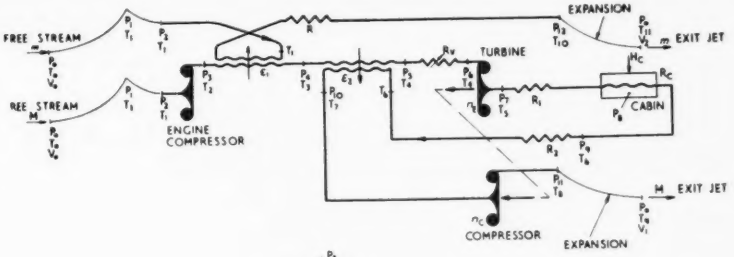
C. Refrigeration Section Including Spill Pressurisation
- (*i*) Pressure drop for heat rejection from charge side of exchanger.
- (*ii*) Pressure drop for flow and temperature control valves.
- (*iii*) Turbine loss.
- (*iv*) Pressure drop for heat pick-up from compartment.
- (*v*) Entropy increase for spill pressurisation.
- (*vi*) Duct loss to cooling side of exchanger.
- (*vii*) Pressure loss for heat transfer to cooling side of exchanger.
- (*viii*) Pressure loss of feed duct to braking compressor.
- (*ix*) Entropy increase of re-compression.
- (*x*) Final expansion, and exit jet loss.

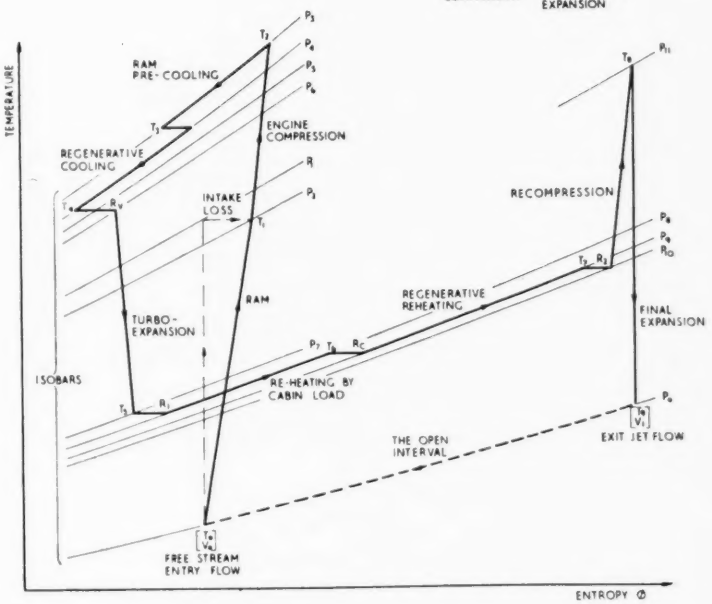
The detailed analysis of installational losses has to be related to particular systems. For the regenerative, the method of Appendix I can readily be extended to provide such quantitative assessments. One typical case has been worked out for $M_0 = 2{\cdot}5$ making allowance for these losses and taking representative engine supply conditions. The calculated c.o.p. was 0·0625 or a power input to heat extraction ratio of 16:1. This will be referred to in a later comparison. Fig. 12(*a*) shows a qualitative representation of various losses on a $T-\phi$ diagram.

An indication of specific power requirements for two major items, namely spill pressurisation and ducting pressure drop, may be obtained from Figs. 13 and 14. In these graphs it is presupposed that distributed duct losses can be represented by an equivalent pressure drop relative to base datum pressure, or as additive to the compartment pressure differential. If the spill is to free stream static, then the base pressure corresponds with the aircraft altitude scale shown on the graphs.*

*For a regenerative system, base datum pressure is at entry to cooling side of heat exchanger.

FIGURE 12(*a*). Engine fed regenerative system.





The grid of pressure ratio lines determine minimum compression ratio necessary for the specified pressure drop. At a given compression ratio the power is constant as spill air temperature is taken at 308°K throughout*.

5. Closed and Semi-Closed Air Cycles

5.1. THE CLOSED AIR CYCLE

This is a reversion to one of the early mechanical refrigerators of textbook fame, namely, the Bell-Coleman machine which utilised an expansion cylinder coupled to a reciprocating compressor.

For aircraft applications either radial or axial flow units would be used, thereby eliminating most of the troubles associated with the original design.

An outline of a single stage scheme with heat rejection to fuel is shown in Fig. 15, the theoretical working with practical efficiencies is given in Appendix II. As this scheme has not so far been applied to aircraft it is worthy of detail consideration since there are several interesting features.

(*i*) To begin with, whereas in an open cycle the compressor and turbine have to be matched for equal shaft power, in a closed cycle of this type the matching is generally for equal pressure ratios. This requires augmenting power for compression to be supplied by an external agency.

(*ii*) Assuming constant speed drive, say by direct coupling to a 400 cycle a.c. motor, then for constant refrigeration output the base pressure P_0 has to be maintained constant. A small charging feed via a pressure regulator would be necessary to compensate for stray leakages.

(*iii*) At constant speed driving good heat transfer efficiency and high refrigeration capacity combined with low pressure losses can be obtained by designing for high base pressure.

(*iv*) In a given system cooling can readily be adjusted to requirements, with economy in power consumption, by varying base pressure. Moreover, at high altitudes, refrigeration can almost be eliminated and power demand substantially reduced by opening the base line to a low pressure region.

Such a refrigerator is obviously suitable for intermittent high rates of cooling and quiescent economy working in between, this being achieved without recourse to by-passing or dumping as in open cycles.

(*v*) With a direct drive by electric motor the provision of ground cooling is simplified.

(*vi*) For sealed compartment direct circulation of the charge air is possible thereby dispensing with the load heat exchanger.

The coefficients of performance for crew and equipment recirculation cooling are given in Fig. 6 and Fig. 10 as 0·33 and 0·56 respectively. These compare unfavourably with Freon vapour machines which are fuel cooled. However, in specific applications, or on detailed analysis of all relevant factors, it may well turn out that a closed air cycle system has an advantage relative to an equivalent vapour system, particularly if cooling by fuel is excluded.

In the Mach number range above 2 to 2·5, the closed air cycle, even theoretically, is more efficient than the best open cycle considered. It has advantages in respect of low operating pressure ratio, ease of control, and moisture elimination.

5.2. SEMI-CLOSED OR "LEAKY" AIR CYCLE

A variant scheme, where a combined output of air for pressurising and a high rate of cooling is required, is the semi-closed or "leaky" air cycle. Basically this would function as a closed cycle extracting heat by direct circulation through the compartment. It would, however, be arranged to have a built-in leak and the necessary small make-up flow for the minimum requirements of pressurising and air conditioning. Such

*For different spill temperature, power loss scales up in the ratio of absolute temperatures.

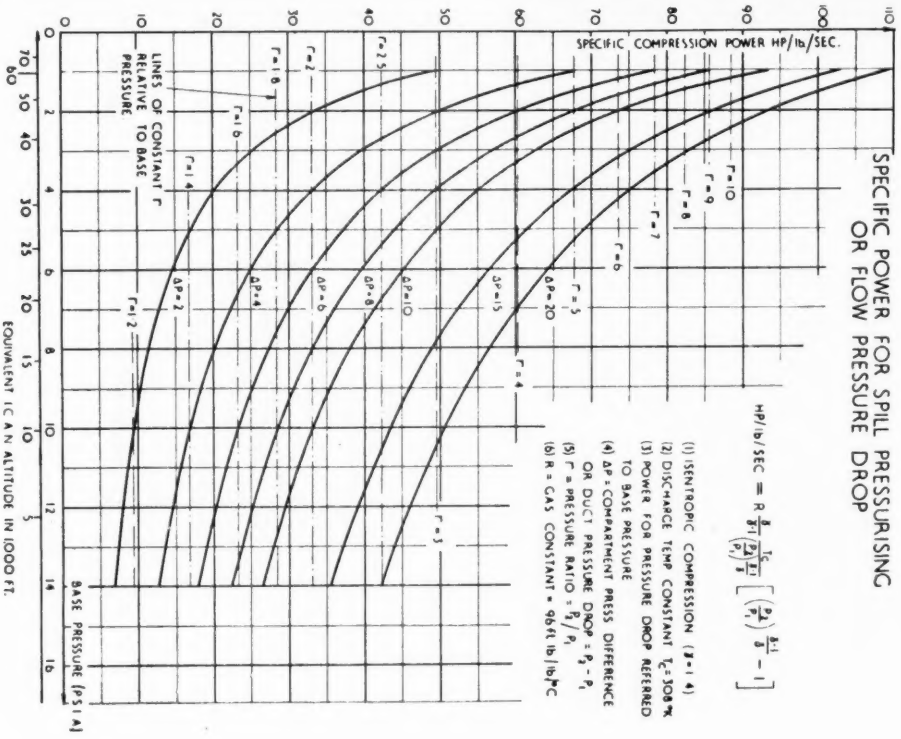

SPECIFIC POWER FOR SPILL PRESSURISING OR FLOW PRESSURE DROP
SPECIFIC COMPRESSION POWER HP/lb/SEC.
HP/lb/SEC = R T1/β−1 (γ−1)/γ [(P2/P1)^((β−1)/β) − 1]
(1) ISENTROPIC COMPRESSION (β = 1·4)
(2) DISCHARGE TEMP CONSTANT T1 = 308°K
(3) POWER FOR PRESSURE DROP REFERRED TO BASE PRESSURE
(4) ΔP = COMPARTMENT PRESS DIFFERENCE OR DUCT PRESSURE DROP = P2 − P1
(5) r = PRESSURE RATIO = P2/P1
(6) R = GAS CONSTANT = 96 ft lb/lb °C
r = 10
r = 9
r = 8
r = 7
r = 6
r = 5
r = 4
r = 3
r = 2·5
r = 2
r = 1·8
r = 1·6
r = 1·4
r = 1·2
ΔP = 20
ΔP = 15
ΔP = 10
ΔP = 8
ΔP = 6
ΔP = 4
ΔP = 2
LINES OF CONSTANT RELATIVE TO BASE PRESSURE
BASE PRESSURE (P.S.I.A)
EQUIVALENT I.C.A.N. ALTITUDE IN 1000 FT.

FIGURE 13.

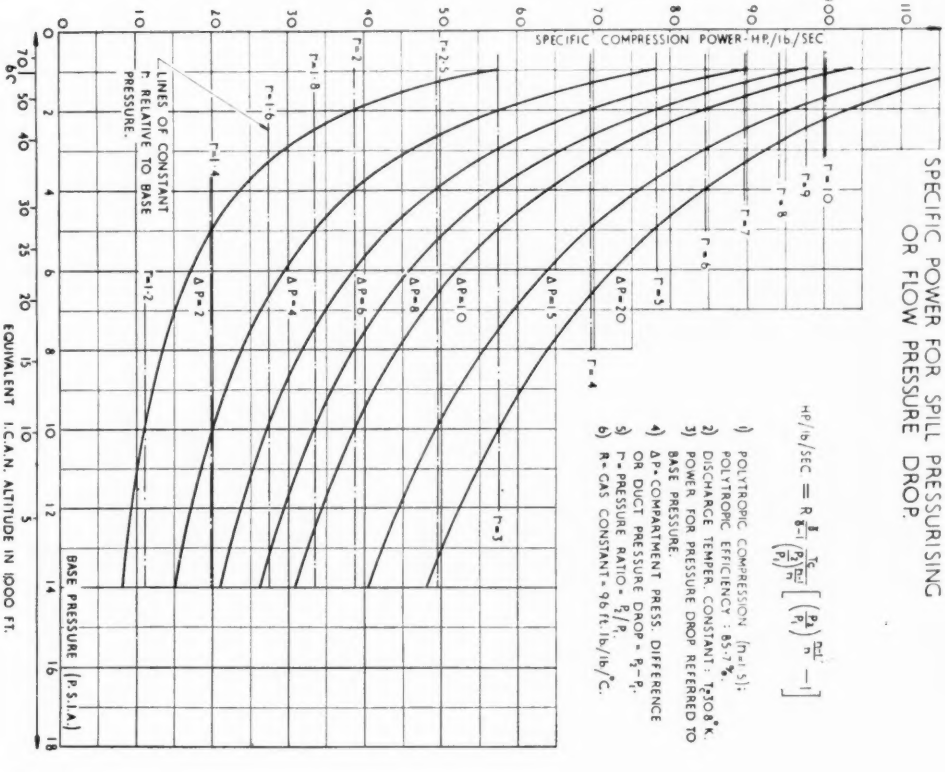

SPECIFIC POWER FOR SPILL PRESSURISING OR FLOW PRESSURE DROP.
SPECIFIC COMPRESSION POWER - HP/lb/SEC
HP/lb/SEC = R T1/β−1 (γ−1)/γ [(P2/P1)^((n−1)/n) − 1]
1) POLYTROPIC COMPRESSION (n = 1·5).
POLYTROPIC EFFICIENCY : 85·7%.
2) DISCHARGE TEMPER. CONSTANT: T1 = 308° K.
3) POWER FOR PRESSURE DROP REFERRED TO BASE PRESSURE.
4) ΔP = COMPARTMENT PRESS. DIFFERENCE OR DUCT PRESSURE DROP = P2 − P1.
5) r = PRESSURE RATIO = P2/P1.
6) R = GAS CONSTANT = 96 ft. lb/lb/°C.
r = 10
r = 9
r = 8
r = 7
r = 6
r = 5
r = 4
r = 3
r = 2·5
r = 2
r = 1·8
r = 1·6
r = 1·4
r = 1·2
ΔP = 20
ΔP = 15
ΔP = 10
ΔP = 8
ΔP = 6
ΔP = 4
ΔP = 2
LINES OF CONSTANT r RELATIVE TO BASE PRESSURE.
BASE PRESSURE (P.S.I.A.)
EQUIVALENT I.C.A.N. ALTITUDE IN 1000 FT.

FIGURE 14.

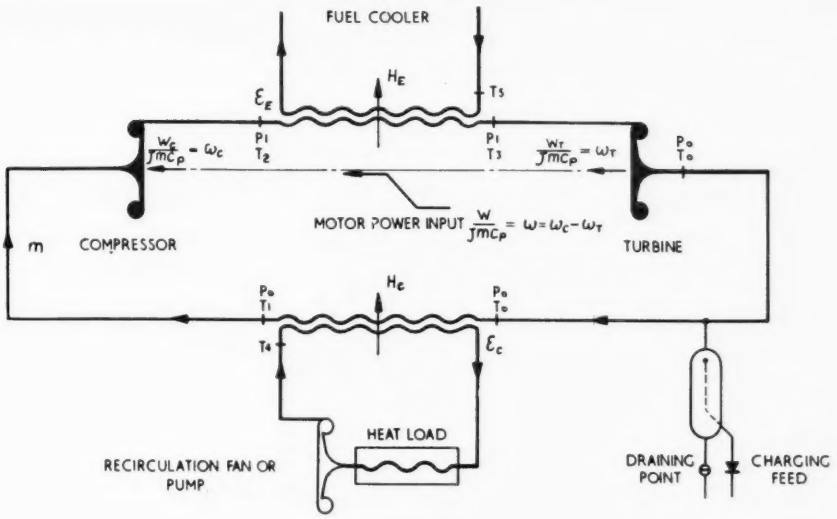


FIGURE 15. Motorised closed "air" cycle. Heat rejection to fuel.

make-up flow would be pre-cooled by fuel or liquid refrigerant as indicated in Fig. 16.

A high rate of circulation relative to make-up flow rate, say about 10 : 1, would provide efficient heat transfer and a c.o.p. approaching that of a closed air cycle. The augmenting flow may be stepped up in the event of partial loss of compartment pressure, and motorisation again simplifies the problem of ground cooling.

By suitable layout or packaging of components it would be possible to obtain a high cooling load from compact radial flow units with relatively low pressure ratios and small pressure losses. This would reduce disparity in overall power requirement relative to a vapour cycle installation.

Like the open regenerative cycle it has some disadvantages associated with interposition of the cooled compartment between the turbine and compressor.

6. Closed Vapour Cycles

6.1. THE BASIC CYCLE

The Vapour-Liquid refrigeration machine is the nearest practical approach to a reversed Carnot engine. The main departures are (*i*) introduction of some superheat during compression and (*ii*) use of throttling process instead of adiabatic expansion. Both modifications are for the convenience of avoiding wet processes within the machine.

The cycle is shown on a pressure total heat diagram in Fig. 17. This is the most convenient mode of representation for performance estimation purposes.

In the ideal case we start with dry saturated vapour at T_1, P_1 and compress isentropically to T_2', P_2 producing vapour of superheat $T_2' - T_2''$. This is followed by heat rejection at constant pressure, first the superheat is removed then the substance is condensed isothermally rejecting its latent heat $H_2'' - H_3$. The next process is throttling at constant total heat ($H_3 = H_4$) down to T_1, P_1 when partial re-evaporation takes place. Finally complete re-evaporation to the initial state T_1, P_1 by absorption of the heat load.

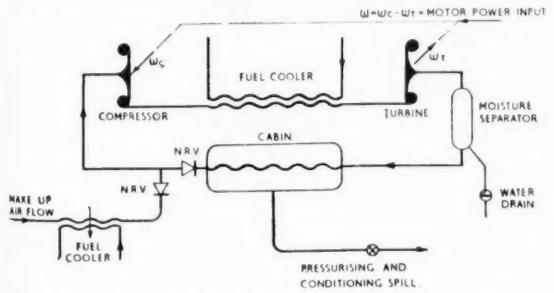


FIGURE 16. Semi-closed or leaky air cycle. For compartment pressurising, conditioning and cooling.

The estimation of c.o.p. taking into account compression efficiency is indicated in Fig. 17.

Figure 18 is a line diagram of a vapour cycle refrigerator as may be applied to aircraft duties. It incorporates a radial compressor and fuel cooling for the condenser, a condensate receiver upstream of the expansion valve, and recirculation fan or pump for heat rejection to the evaporator.

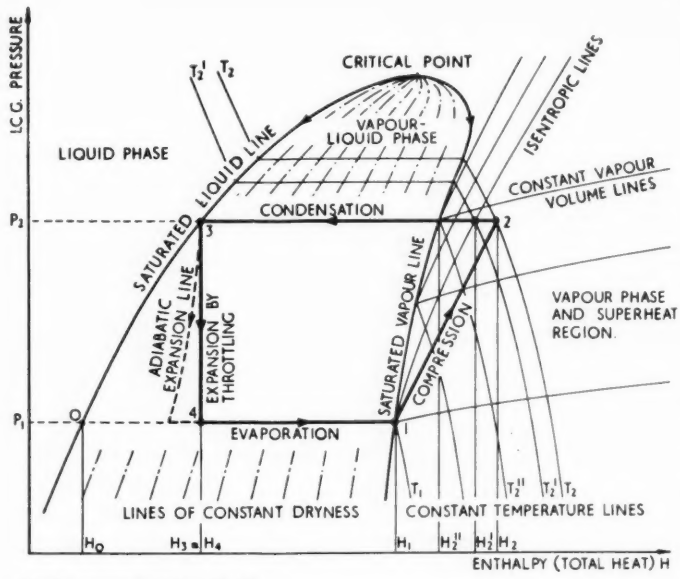
By virtue of its approach to a reversed Carnot engine, the vapour refrigerator would have a relatively high c.o.p. which in a restricted sense would be largely independent of the thermodynamic properties of the particular refrigerant.

In practice, of course, a high critical temperature, large value of latent heat combined with steep slopes of the saturation lines on either side of critical point, together with corresponding steepness of adiabatic lines, all make for efficient working. Further, in aircraft applications, chemicals and toxic innertness are essential requirements, and this narrows the list of suitable refrigerants down to the family of Freons (British Arctons) or water. The latter is mainly suitable as an intermediate coolant or expendable refrigerant in situations where cooling by fuel is excluded.

Tabulated results of cycle computations for Freon 12 and Freon 21 are given in Appendix III. Freon 12 gives a higher refrigeration performance and lower pressure ratios, but the absolute operating pressures are much higher than for Freon 21. The gain in performance is, therefore, likely to be offset by increased overall system weight.

6.2. COMPOSITE RAM AIR AND VAPOUR CYCLES

A typical example of compounding an air and a vapour cycle for low temperature output which, at the



Cycle pressure ratio: P_2/P_1
Cycle temperature ratio: T_2/T_1
Superheat at compressor delivery: T_2-T_2''
Superheat at compressor entry: O

$$\text{Compression work} = \text{cycle work} = H_2-H_1 = \frac{H_2'-H_1}{\text{Adiabatic eff. of compression}}$$

Heat extracted: H_1-H_4
Heat rejected: H_2-H_4

$$\text{Coefficient of performance} = \frac{\text{Heat extracted}}{\text{Cycle work}} = \frac{H_1-H_4}{H_2-H_1}$$

FIGURE 17. Vapour cycle refrigeration work diagram.

same time, avoids the use of either fuel or a total loss refrigerant as heat sinks is shown in Fig. 19.

This comprises a reverse flow bootstrap cascaded on to a single stage vapour cycle for heat rejection purposes. Each of these sections is a high performance element in its own domain.

When the individual c.o.p.'s for the specified duty are known the resultant c.o.p. can readily be estimated analytically. A typical performance curve is given in Fig. 19 for crew cooling duty. As would be expected the resultant c.o.p. varies with Mach number.

The scheme is in a sense an alternative to the regenerative cycle, avoiding most of its disadvantages and yielding relatively high c.o.p. in the Mach number range to 2·5, but it is obviously heavier and bulkier than a single-stage air or vapour refrigerator.

7. General Appraisal

We have now compared the performance of a fairly representative range of possible refrigerators for high Mach number flight and, to consolidate the data obtained, the difficult task of some appraisal in relation to practical aircraft requirements will be attempted.

As for other design situations, performance alone is not the sole criterion of merit. Indeed it may be said that each of the relatively simple basic types considered, and numerous other variants, have their range of applicability to aircraft cooling duties. The most that can be done here is to indicate some of the factors which may restrict the final choice of system in specific situations from an extensive field of possibilities.

7.1. VAPOUR VERSUS AIR CYCLES

Other considerations apart, the aim of the aircraft designer is always that of maximising performance with respect to weight. Although performance-wise the vapour cycle is advantageous at high Mach numbers, with currently available equipment it is heavier than an equivalent air cycle, in a five-fold ratio or more. In terms of weight drag power, this represents an appreciable penalty tending to depress its effective c.o.p. (*see* Fig. 20 for approximate weight drag power). Further, where for operational or safety requirements the only permitted heat sink is ram air, and compounding with an air cycle component is necessary, its net performance advantage may well degenerate to dead weight liability.

Yet another aspect, where a final output of pressure air coolant is required, concerns the percentage spill flow necessary in the particular application. If the ratio of spill to total cooling flow is high no case can be made out for using a vapour cycle. Examples of such applications are (*i*) direct personnel body cooling by separate supply to pressurised/refrigerated garment, (*ii*) transparency exterior cooling, (*iii*) gun, ammunition, and fuel tank bays, with potential build-up of explosive gas concentrations.

In crew compartment conditioning of military aircraft the overall requirements again largely off-set the advantages of using a vapour cycle for the cooling duty.

Generally speaking a case can be made out in favour of the vapour cycle for the following applications: —

(*i*) Total re-circulation systems with air or water as the final coolant.

(*ii*) Centralised refrigeration utilising a buffer heat transport medium with local re-circulation of final coolant.

(*iii*) Transport aircraft with motorised built-in equipment for high duty pre-cooling on the ground.

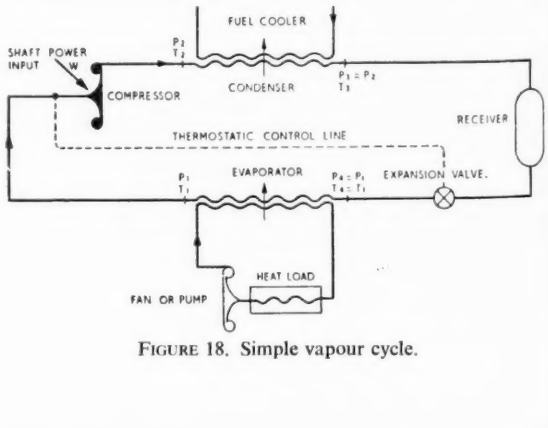


FIGURE 18. Simple vapour cycle.

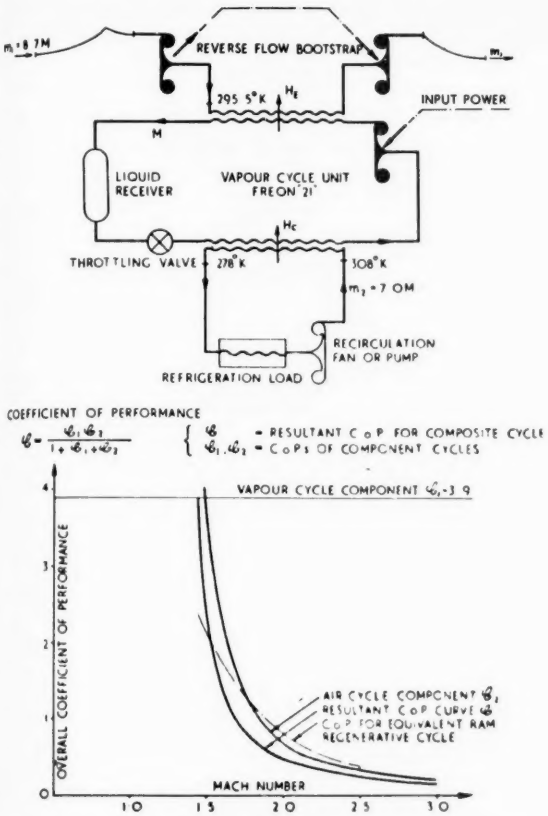


FIGURE 19. Composite ram-air and vapour cycle. Low temperature cooling, and heat rejection to ram-air. Values are given for a typical case.
Mass ratios chosen to provide approximately thermal ratios of 0·8 at each heat exchanger.

7.2. AIR CYCLES

Although air cycles are extravagant in power demand they possess two cardinal redeeming features, namely (*i*) high specific output from compact light weight units and, (*ii*) direct output of air for both cooling and spill pressurisation.

To obtain anything like the order of c.o.p.'s quoted in this paper it is necessary to apply the package concept, with all components, ductings, and controls designed for optimum efficiency, and located in proximity to the heat load. This is not surprising when we consider that no self-respecting engine designer would contemplate doing otherwise for the main power unit, and the air cycle refrigerator is merely a reversed heat engine on a smaller scale.

In the matter of choice, particularly where an internal heat sink is available and 100 per cent spill is required, the basic bootstrap provides the most latitude both functionally and in respect of cooling potential over a wide flight speed range. A particular application is for crew compartment cooling in high speed flight where, for short endurance, inter-stage heat rejection to ducted ram air and an augmenting water boiler may be used.

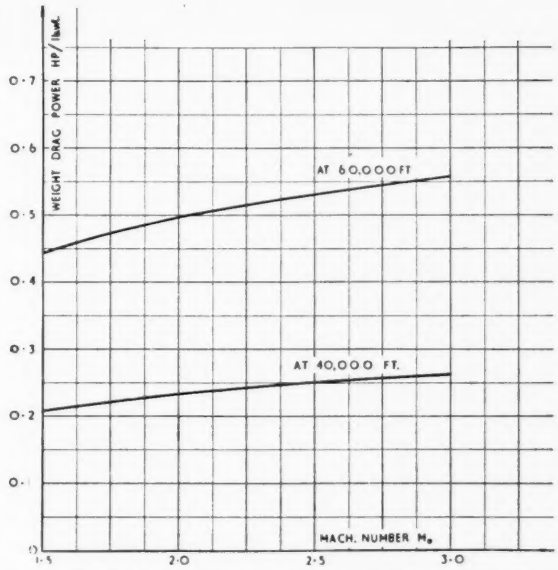


FIGURE 20. Weight drag power plotted against Mach number for typical supersonic fighter.

For 100 per cent air re-circulation to sealed equipment compartments, the closed air cycle with a hydraulic or electric motor drive and heat rejection to fuel is an obvious first choice.

From an efficiency aspect, the regenerative and the reverse flow bootstrap appear to be the best of open cycles considered. This is on account of their heat engine component which predominates at low cooling levels.

For crew cooling the regenerative system poses a number of installational and functional difficulties, *i.e.* large heat exchanger, need for stabilising cabin pressure, and so on. There is, further, the serious effects of stray cabin leakages on performance which may involve special safeguards such as the inclusion of an augmenting fuel or water evaporative cooler.

A detailed comparison taking into account practical duct, heat exchange, and pressurisation losses, for both the engine fed regenerative system and the semi-closed air cycle at $M_0 = 2{\cdot}5$ is set out in Appendix IV. This shows that the best practical c.o.p.'s are approximately 0·0625 and 0·219 respectively when all power demands are included. The example given represents approximately the crew cooling requirements for a supersonic fighter with a Mach number of 2·5.

8. Concluding Remarks

In focusing attention on the main theme of refrigeration, it has been necessary for the sake of cogency to overlook many subsidiary but also important problems, such as the various aspects of heat exchange, considerations of system design, component matching and system control. Each of these subjects is by itself quite extensive. However, it is hoped that in aiming at the core of the refrigeration problem a wider interest in this field has been stimulated.

ACKNOWLEDGMENTS

The paper represents a crystalisation of some work done at Hawker Aircraft Limited, augmented with background information from equipment suppliers.

The author would like to express thanks to Sir Sydney Camm, C.B.E., F.R.Ae.S., Director and Chief Designer, for his encouragement and sponsorship of this paper. The opinions and analytical procedures are the author's and do not necessarily reflect either the Company's technical policy or design practice.

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APPENDIX I

RAM REGENERATIVE CYCLE PERFORMANCE ANALYSIS

Optimum Working for a Range of Refrigerators

1. INTRODUCTORY NOTE

The following analysis of the regenerative system is given as typical of the method and assumptions used for deriving the performance of various open cycles.

2. DIAGRAM OF SYSTEM AND STATION PARAMETERS

See Fig. 21.

3. THE TEMPERATURE—ENTROPY DIAGRAM

See Fig. 22.

4. NOTATION

c_p specific heat at constant pressure

$\varepsilon = \dfrac{T_1 - T_2}{T_1 - T_4}$ heat exchange thermal ratio

g gravitational acceleration

γ ratio of specific heats = 1·4

H_c heat rejected from cabin

h_c cabin temperature change (°C) $= T_4 - T_3$

H_E heat rejected in primary cooler

h_E temperature change through heat exchanger (°C) $= T_1 - T_2 = T_5 - T_4$

J mechanical equivalent of heat

λ intake total head pressure recovery $= P_2/P_1$

m mass flow rate of air

M_0 free stream Mach number

n_c compressor index of polytropic compression $= \dfrac{\gamma}{\gamma - 1}\eta_c$

η_c polytropic efficiency of compression

n_E turbine index of polytropic expansion $= \dfrac{\gamma}{\gamma - 1} \times \dfrac{1}{\eta_E}$

η_E polytropic efficiency of expansion

P pressure (abs.)

R gas constant

T temperature (°K)

V velocity (ft./sec.)

w weight flow rate of air

5. MAIN ASSUMPTIONS

(*a*) γ, n_E and n_c constant.

(*b*) Duct pressure losses neglected except for ram duct.

(*c*) Duct heat leakage losses neglected.

(*d*) Cabin pressure according to system working level.

(*e*) Cabin flow leakage neglected. Hence ε is constant at optimum value.

(*f*) System free-running at maximum working for the specified Mach number and altitude.

(*g*) Intake pressure recovery factor λ as tabulated assumes single, double or triple shock configuration, according to Mach number.

(*h*) T_3 and h_c constant throughout.

(*i*) Isentropic expansion from P_1 to exit jet.

(*j*) Dynamic head in ducts is negligible.

6. THEORETICAL ANALYSIS OF THE SYSTEM

(*a*) Station parameters as shown in Table I.

(*b*) Momentum drag power: $\pi_m = \dfrac{w}{g} V_0 (V_0 - V_1)$

(*c*) Composite cycle net work rate = kinetic energy change rate $= \dfrac{w}{g}\left(\dfrac{V_0^2}{2} - \dfrac{V_1^2}{2}\right)$

(*d*) Coefficient of performance =

$$\frac{\text{power equivalent of heat removed by refrigeration section}}{\text{net cycle work rate}} = \frac{JH_c}{\dfrac{w}{g}\left(\dfrac{V_0^2}{2} - \dfrac{V_1^2}{2}\right)}$$

(*e*) Overall coefficient of performance =

$$\frac{\text{power equivalent of heat removed by refrigeration section}}{\text{momentum drag power}} = \frac{JH_c}{\dfrac{w}{g} V_0 (V_0 - V_1)}$$

TABLE I

Station Reference P	T	V	P	T	V
0	0	0	P_0	T_0	$V_0 = M_0\sqrt{(\gamma g R T_0)}$
1	1	0	$P_1 = P_0\left(\dfrac{T_1}{T_0}\right)^{3.5}$	$T_1 = T_0\left(1 + \dfrac{M_0^2}{5}\right)$	0
2	1	0	$P_2 = \lambda P_1$	T_1	0
2	2	0	P_2	$T_2 = (1-\epsilon)T_1 + \epsilon T_4$ $= (1-\epsilon)T_1 + \epsilon(T_3 + h_c)$	0
3	3	0	$P_3 = P_2\left(\dfrac{T_3}{T_2}\right)^{n_E}$	T_3 Given	0
3	4	0	P_3	$T_4 = T_3 + h_c$	0
3	5	0	P_3	$T_5 = (T_1 - T_2) + T_4$	0
4	6	0	$P_4 = P_3\left(\dfrac{T_6}{T_5}\right)^{n_c}$	$T_6 = (T_2 - T_3) + T_5$	0
0	7	1	P_0	$T_7 = T_6\left(\dfrac{P_0}{P_4}\right)^{2/7}$	$V_1 = \sqrt{\{2Jgc_p(T_6 - T_7)\}}$

$H_c = mc_p h_c = mc_p (T_4 - T_3)$ $\quad H_E = mc_p h_E = mc_p (T_5 - T_4)$

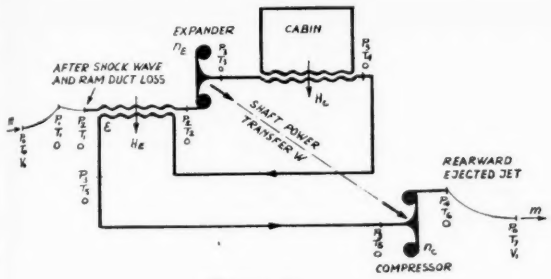


FIGURE 21.

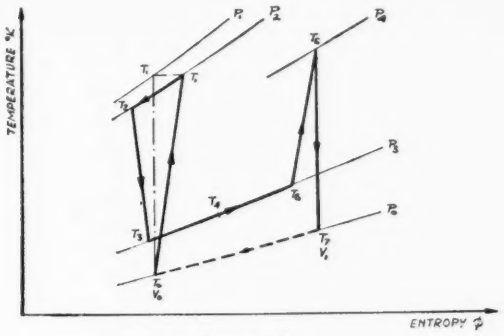


FIGURE 22.

7. TABULATED RESULTS

Common fixed data

$\varepsilon=0{\cdot}6, n_E=4{\cdot}5, n_c=2{\cdot}5, T_3=278°\text{K}$,
$w=1$ lb./sec., $h_c=30°\text{C}$.

Case 1. Sea level I.C.A.N.
$P_0=14{\cdot}7$ lb./in.^{2} abs., $T_0=288°\text{K}$. *See* Table II.

Case 2. Tropopause I.C.A.N. (36,000 ft.)
$P_0=3{\cdot}297$ lb./in.^{2} abs., $T_0=216{\cdot}5°\text{K}$. *See* Table III.

APPENDIX II

MOTORISED CLOSED CYCLE

Air Charged—Heat Rejection to Fuel

1. INTRODUCTORY NOTE

The following analysis sets out the method and assumptions used for deriving the performance of the closed air cycle. The computations cover both direct recirculation, and the use of a buffer heat exchanger.

2. DIAGRAM OF SYSTEM AND STATION PARAMETERS
See Fig. 23.

3. TEMPERATURE-ENTROPY DIAGRAM
See Fig. 24.

4. NOTATION

c.o.p. coefficient of performance

$$=\frac{T_1-T_0}{(T_2-T_3)-(T_1-T_0)}=\frac{h_c}{\omega}$$

c_p specific heat at constant pressure

ε_c thermal ratio of heat absorber

$$=\frac{T_1-T_0}{T_4-T_0}=\frac{h_c}{T_4-T_0}$$

ε_E thermal ratio of heat rejector

$$=\frac{T_2-T_3}{T_2-T_5}$$

g gravitational acceleration

h_c temperature rise for heat load H_c

$$=\frac{H_c}{mc_p}=T_1-T_0$$

h_E temperature drop for fuel cooling rate H_E

$$=\frac{H_E}{mc_p}=T_2-T_3$$

J mechanical equivalent of heat
m air mass flow rate in refrigerator
n_c index of polytropic compression
n_E index of polytropic expansion
P pressure absolute
r cycle pressure ratio $=\frac{P_1}{P_0}=\left(\frac{T_2}{T_1}\right)^{n_c}=\left(\frac{T_3}{T_0}\right)^{n_E}$
T temperature (°K)
ω specific motor power input (°C)

$$=\frac{W}{Jmc_p}=\frac{W_c-W_E}{Jmc_p}=(T_2-T_1)-(T_3-T_0)$$

TABLE II

M_0 / λ	1 / 0·95	1·25 / 0·95	1·50 / 0·9339	1·75 / 0·912	Allowing 0·95 subsonic intake efficiency
number of shocks for λ	1	1	1	2	
$w/g\times V_0^2/2$ h.p.	35·2	55	79·3	107·9	
$w/g\times V_1^2/2$ h.p.	14·5	28·8	44·5	62·1	
$\frac{w}{g}V_0(V_0-V_1)=\pi_m$ h.p.	25·2	30·4	39·8	52·1	
cycle work h.p.	20·7	26·2	34·8	45·8	
JH_c h.p.	18·3	18·3	18·3	18·3	
c.o.p.	0·885	0·699	0·526	0·40	
overall c.o.p.	0·726	0·603	0·460	0·352	

TABLE III

M_0 / λ	1·75 / 0·912	2 / 0·8588	2·25 / 0·798	2·5 / 0·7144	2·75 / 0·7695	3 / 0·708
number of shocks for λ	2	2	2	2	3	3
$w/g\times V_0^2/2$ h.p.	81·2	105·9	134·2	165·5	200·5	238·6
$w/g\times V_1^2/2$ h.p.	67·9	84·3	101·6	119·1	144·8	169·5
$\pi_m=\frac{w}{g}V_0(V_0-V_1)$ h.p.	13·9	23·0	34·8	50·2	60·2	75·0
cycle work h.p.	13·3	21·6	32·6	46·4	55·7	69·1
JH_c h.p.	18·3	18·3	18·3	18·3	18·3	18·3
c.o.p.	1·377	0·848	0·563	0·395	0·329	0·265
overall c.o.p.	1·319	0·797	0·526	0·365	0·304	0·244

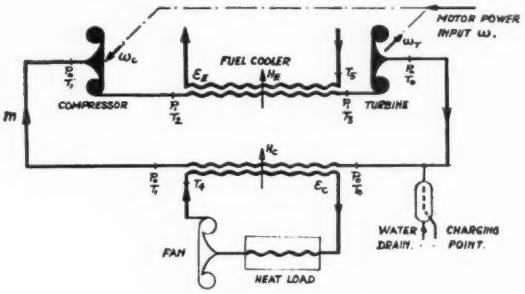


FIGURE 23.

ω_c specific compressor power input (°C)
$$= \frac{W_c}{Jmc_p} = T_2 - T_1$$

ω_T specific turbine shaft power output (°C)
$$= \frac{W_T}{Jmc_p} = T_3 - T_0$$

5. MAIN ASSUMPTIONS
(*a*) Heat exchange and duct pressure drops neglected.
(*b*) Heat leakage losses neglected.

6. ANALYTICAL RELATIONS

$$\varepsilon_c = \frac{T_1 - T_0}{T_4 - T_0}, \varepsilon_E = \frac{T_2 - T_3}{T_2 - T_5}, h_c = T_1 - T_0, T_2 = T_1 r^{1/n_c}, T_3 = T_0 r^{1/n_E}.$$

These relations yield an equation for r in terms of the specified temperatures and thermal ratios which can be solved graphically. Thereafter, the remaining cycle temperatures and the c.o.p. may be computed.

7. WORKED OUT NUMERICAL VALUES
Common fixed data

$n_c = 2{\cdot}5$, $n_E = 4{\cdot}5$, $\varepsilon_E = 0{\cdot}8$, $h_c = 30°\text{C}$, $T_5 = 323°\text{K}$

Case 1. Crew compartment direct recirculation cooling With no heat exchanger $\varepsilon_c = 1$ or $T_4 = T_1$. Given $T_0 = 278°\text{K}$

Case 2. Equipment direct recirculation cooling

$T_4 = T_1 = 333°\text{K}$

Case 3. Equipment cooling by heat exchanger $\varepsilon_c = 0{\cdot}8$, $T_4 = 333°\text{K}$

8. TABULATED RESULTS
See Table IV.

TABLE IV

Parameter	*Crew*	*Equipment*	
	Direct Circulation Case 1	*Direct Circulation Case 2*	*With Heat Exchanger Case 3*
r	2·95	1·7	1·98
T_0 (°K)	278	303	295·5
T_1 (°K)	308	333	325·5
T_2 (°K)	474·5	412	428
T_3 (°K)	353·5	341	344
c.o.p.	0·33	0·74	0·56

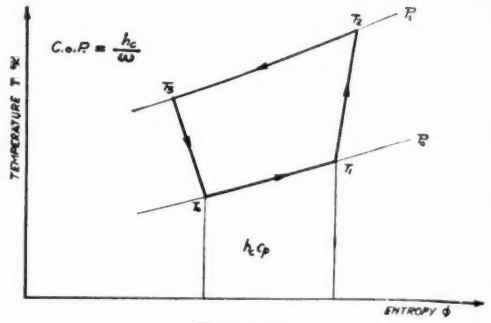


FIGURE 24.

APPENDIX III

VAPOUR CYCLE PERFORMANCE ANALYSIS

1. INTRODUCTORY NOTE
The following analysis gives the method and assumptions used for deriving the performance of the simple vapour cycle.

2. DIAGRAM OF SYSTEM AND STATION PARAMETERS
See Fig. 25.

3. THE PRESSURE-ENTHALPY DIAGRAM
See Fig. 26.

4. NOTATION
c.o.p. coefficient of performance as refrigerator
η_c adiabatic efficiency of compression $= \dfrac{H_2' - H_1}{H_2 - H_1}$

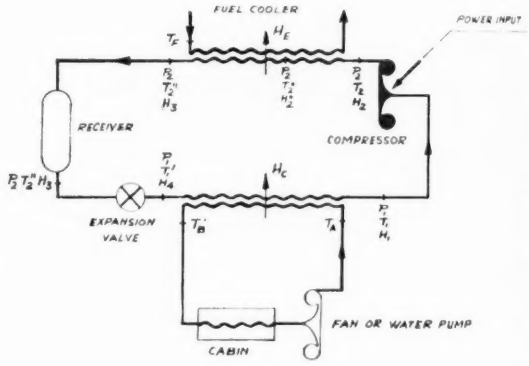


FIGURE 25.

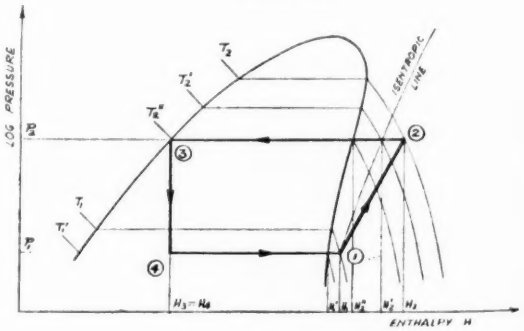


FIGURE 26.

ε_F heat exchange thermal ratio for fuel cooler

$$= \frac{T_2 - T_2''}{T_2 - T_F}$$

ε_c heat exchange thermal ratio for cabin cooler

$$= \frac{T_A - T_B}{T_A - T_1'}$$

P pressure absolute (p.s.i.)

T temperature

T_F fuel temperature

5. MAIN ASSUMPTIONS

(*a*) c_p, η_c, ε constant throughout.

(*b*) Duct and heat exchanger pressure losses neglected.

(*c*) Duct heat leakages neglected.

(*d*) Compressor entry superheat taken at 10°F.

(*e*) Throttling is at constant enthalpy.

(*f*) No undercooling.

6. REQUIRED RESULTS

(*a*) All station parameters: *i.e.* $P_1 - P_2$; $T_1 - T_3$; $H_1 - H_4$.

(*b*) Pressure ratio $= r = \frac{P_2}{P_1}$.

(*c*) Coefficient of performance $= \frac{\text{heat extracted}}{\text{work done}} = \frac{H_1 - H_4}{H_2 - H_1}$

7. RESULTS OF TYPICAL CALCULATIONS

Common fixed data

$\varepsilon_c = \varepsilon_E = 0{\cdot}8$; $\eta_c = 0{\cdot}68$; $T_A - T_B = 30°C$; $T_F = 323°K$; $T_1 - T_1' = 10°F$

Case 1. Crew compartment cooling, $T_A = 555°R$ (95°F)

(*a*) Freon 21. (*b*) Freon 12.

Case 2. Equipment bay cooling, $T_A = 600°R$

(*a*) Freon 21. (*b*) Freon 12.

See Table V.

TABLE V

Parameter	*Case 1 Crew Compartment Cooling*		*Case 2 Equipment Bay Cooling*	
	(*a*) *Freon 21*	(*b*) *Freon 12*	(*a*) *Freon 21*	(*b*) *Freon 12*
T_1 (°F)	37·5	37·5	82·5	82·5
$T_1' = T_4$	27·5	27·5	72·5	72·5
T_2	300·0	187·0	221·5	158·0
T_2'	229·0	153·0	184·0	141·0
$T_3 = T_2''$	157·0	135·0	142·0	129·0
T_F	122	122	122	122
H_1 (B.Th.U./lb.)	123·8	82·2	129·5	87·3
H_2	160·9	101·0	148·5	96·4
H_2'	149·0	95·0	142·4	93·5
H_2''	137·0	92·0	136·0	92·7
H_3	50·0	41·0	45·8	39·0
H_4	50·0	41·0	45·8	39·0
P_1 (p.s.i. abs.)	9	41	24	87
P_2	97	205	78	192·5
P_2/P_1	10·78	5	3·25	2·21
c.o.p.	1·989	2·19	4·4	5·31

APPENDIX IV

SUPERSONIC TWO-SEATER FIGHTER

Practical Performance Calculations for Alternative Systems of Crew Cooling

Design Data

Aircraft

$M_0 = 2{\cdot}5$ at 36,000 ft. altitude I.C.A.N.

Intake

Shock loss factor = 0·752. Subsonic total head efficiency = 0·95.

Engine

Compression ratio = 2·43. Temperature ratio = 1·49.

Cabin

Kinetic heat load = 15·3 h.p.
Equipment and internal sources = 3 h.p.
Total heat load = 18·3 h.p.
Air inlet temperature = 5°C
Maximum temperature rise = 30°C; hence required cooling air flow = 1 lb./sec.
Required cabin differential pressure = 5 lb./in.² relative to altitude static. Hence cabin pressure = 8·29 lb./in.² abs.

Specified minimum flow for spill pressurisation and conditioning = 0·1 lb./sec. Hence maximum possible recirculation rate = 0·9 lb./sec.

Statement of the problem

With the specified duty, and taking practicable heat exchange and ducting pressure losses, determine the c.o.p.'s and net power requirements appropriate to various refrigeration schemes as follows:—

Case I.—Regenerative system supplied from the final stage of the engine compressor.

Case II.—Leaky "Air Charged" Cycle cooled by a water boiler which is pressurised to boil-off at +90°C. The augmenting flow to be ram air, turbo-expanded to required outlet pressure. In this case also determine water requirement for 15 minutes duration at $M_0 = 2{\cdot}5$.

Case III.—Leaky "Air Charged" Cycle with fuel cooling at main and augmenting flow. Fuel supply temperature +50°C. Augmenting flow taken from a ram scoop and turbo-expanded to required pressure after pre-cooling.

Case I. Regenerative scheme. See Fig. 27.

Assumed component and ducting performance data

$m = 2{\cdot}5$ lb./sec., $M = 1$ lb./sec.

Ram heat exchanger

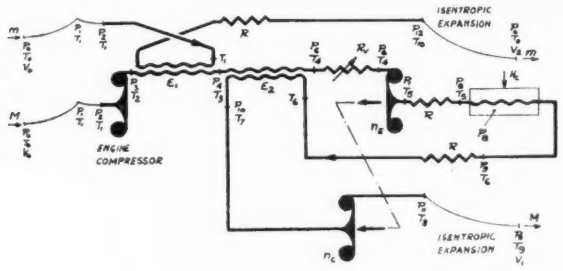
$\varepsilon_1 = 0{\cdot}8$, $P_3 - P_4 = 3$ lb./in.²

$P_2 - P_{12} = 2$ lb./in.²

Regenerative exchanger

$\varepsilon_2 = 0{\cdot}6$, $P_4 - P_5 = 3$ lb./in.²

$P_9 - P_{10} = 3$ lb./in.²



R_v = variable matching throttle to control cabin pressure.
R = symbol representing allowance for heat exchange and ducting pressure drop.
Temperature control by-passes not shown.

FIGURE 27. DIAGRAM OF SYSTEM AND STATION PARAMETERS.

Variable throttle R_v

Adjusts $P_5 - P_6$ to a level which sets $P_8 = P_9 = P_0 + 5$ lb./in.^{2} abs.

Turbine

$n_E = 4{\cdot}5$

Cabin feed duct

$P_7 - P_8 = 4$ lb./in.^{2}

Cabin

$T_5 = 278°$ K, $T_6 = 308°$ K, $P_8 = 8{\cdot}29$ lb./in.^{2} abs.

Compressor

$n_c = 2{\cdot}5$

Final results of computations

C.o.p. (with respect to cycle work, including intake and engine compressor loss) = 0·0625.
Net power required per h.p. of cooling = 16 h.p.
Net total power required = 293 h.p. Equivalent to approximately $\frac{1}{4}$ per cent of engine thrust power for the condition of flight.

Case II. Leaky "air charged" cycle, water cooled. See Fig. 28.

Assumed component and ducting performance data

$M = 1$ lb./sec. $m = 0{\cdot}1$ lb./sec.

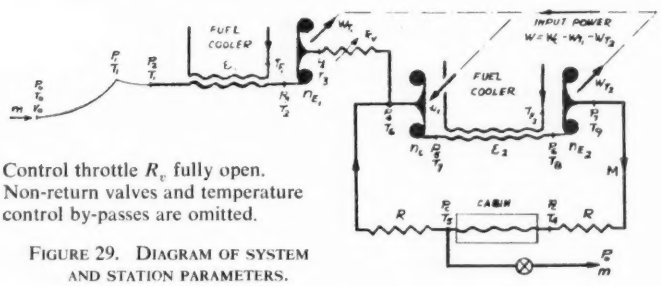
Ram turbine $n_{E_1} = 4{\cdot}5$

Main cycle compressor

$n_c = 2{\cdot}5$

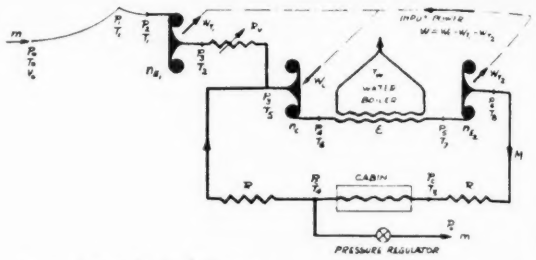
Water boiler

$\varepsilon = 0{\cdot}8$, $T_w = 363°$ K, $P_4 - P_5 = 3$ lb./in.^{2} (including ducts)



Control throttle R_v fully open.
Non-return valves and temperature control by-passes are omitted.

FIGURE 29. DIAGRAM OF SYSTEM AND STATION PARAMETERS.



Control throttle R_v fully open.
Non-return valves and temperature control by-passes are omitted.

FIGURE 28. DIAGRAM OF SYSTEM AND STATION PARAMETERS.

Main cycle turbine $n_{E_2} = 4{\cdot}5$

Cabin feed duct

$P_6 - P_c = 3$ lb./in.^{2}

Cabin

$T_3 = 278°$ K, $T_4 = 308°$ K, $P_c - P_0 = 5$ lb./in.^{2}

Duct to compressor

$P_c - P_3 = 2$ lb./in.^{2}

Final results

c.o.p. basic cycle only = 0·117, c.o.p. complete system = 0·112
Total h.p. for cooling and spill flow = 163 h.p.
Weight of water per 15 min. = 106 lb.

If a stage of pre-cooling is introduced by off-take of expanded air from a higher flow ram turbine, then the water consumption may be reduced to 58 lb., but then the c.o.p. falls to 0·082.

Case III. Leaky "air charged" cycle, fuel cooled. See Fig. 29.

Assumed component and ducting performance data

$M = 1$ lb./sec., $m = 0{\cdot}1$ lb./sec.

Ram fuel cooler

$\varepsilon_1 = 0{\cdot}8$, $T_{F_1} = 323°$ K, $P_2 - P_3 = 2$ lb./in.^{2}

Ram turbine $n_{E_1} = 4{\cdot}5$

Main cycle compressor

$n_c = 2{\cdot}5$

Main fuel cooler

$\varepsilon_2 = 0{\cdot}8$, $T_{F_2} = 323°$ K, $P_5 - P_6 = 3$ lb./in.^{2} (including ducts)

Main turbine $n_{E_2} = 4{\cdot}5$

For cabin system from turbine to compressor, all conditions as in Case II.

Final results

c.o.p. basic cycle only = 0·246, c.o.p. complete system = 0·219.
Total h.p. for cooling and spill flow = 84 h.p.

Complexity and Progress in Transport Aircraft*

by

N. E. ROWE

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(Technical Director, Blackburn and General Aircraft Ltd.)

I count it a signal honour to be invited to give the Rex Pierson Memorial Lecture; he was a great aeronautical engineer, a pioneer with a practical flair and we honour ourselves in honouring his memory. It is also a great personal pleasure, because I had known him from my early days at Martlesham in 1926, and we worked closely and generally in harmony while I was R.T.O. at Weybridge for five years. During that period I was privileged to make many friends here and a visit to Weybridge has always some sense of homecoming for me, although of course there has been such growth that the place is now unrecognisable to a comparative stranger.

There is no doubt that Rex Pierson had a real "feeling" for aeroplanes, a deep perception and almost an instinct for what was right. He had a great awareness of the value of aerodynamic "cleanness," and I think, of all the great designers, he was one of the first to recognise the value of aerodynamics in the practical sense and the great potential value of model testing to the designer. I think those in charge of affairs here today would agree that his vision in this field set a tradition and a pattern which has resulted in Vickers having such first-rate wind tunnel facilities today. He always had a keen interest in air transport economics and contributed a valuable article to the JOURNAL in 1945 dealing with the effect of "Design Factors on Operating Cost," which is well worth reading today.

On the job he was the boss; a large man with big personality and considerable drive; but while on occasions he drove hard he was always human and always simple and straightforward in dealing with the problems on the drawing board; he was prepared to argue and discuss, and rarely dictated. He was often on the shop floor and was familiar with most of the important detail of his aeroplanes. Many of his designs went into use in numbers; they were all good practical flying machines, some outstandingly successful, but all bearing the stamp of his practical engineering approach.

He had a strong sense of humour and when he was enjoying a joke his whole face would beam and he would rub his hands vigorously together. They were large hands, and I remember on one occasion, when we were walking up the path to the Mess Room, hearing a bang and a sudden angry exclamation behind me and looking round to see my official visitor with his bowler banged down over his eyes, very red and angry, and Rex Pierson's great hands just being removed —he in great glee! I can only hope that my contribution this evening will be worthy of him.

1. Introduction

During my five years from July 1929 at Weybridge the amount that was done was amazing, although the technical and design staffs were microscopic by present-day standards. The types included Vimy, Virginia, Victoria, B.19/27 Night Bomber—all of these were twin-engined—Type 163, 4-engined Night Bomber, a P.V. with tandem engines; Vespa, Vildebeeste Torpedo Bomber and other roles, C.O.W. Gun Fighter, G.4/31 Reconnaissance Bomber (2 versions)—all of these were single engined military machines; Viastra, passenger carrier, Vellore and Vellox Freighters—twin-engined civil aircraft, although Viastra first flew with three engines. All were biplanes with the exception of the C.O.W. Gun Fighter, the Viastra and the second prototype G.4/31 which were monoplanes. Incidentally, the G.4/31 was the first example of geodetic construction, the fuselage being so constructed. My recollection is that Mr. Wallis was responsible for the structural design of this aircraft which had an unusually large aspect ratio. It became the Wellesley, had a most honourable career in the R.A.F. and of course held the world's long distance record for many years.

I think the B.19/27, the Type 163, C.O.W. Gun Fighter, G.4/31, Viastra, Vellore, were all begun, brought to first flight and well on in development during this time. I remember the Vellore was begun in a Design Office at Vickers, Crayford, because Weybridge could not take it on, and Viastra was brought to the stage of C. of A. and a sale to the King's Flight during my time, much of the building being done at Vickers Supermarines.

Little was done to the Vimy, but Virginia and Victoria went through several Marks, including re-engining with air-cooled in place of Napier Lion engines, conversion to metal from wooden structure and so on. Vildebeeste was re-engined, almost completely re-designed structurally and in lay-out, equipped and flown with floats, as also was Vellore. Vespa was re-engined and obtained a height record.

It is an amazing record for five years, for a total staff—D.O., Stress, Aerodynamics, Mechanical Test, and so on—which could never have exceeded 80 to 100, and much of the time was considerably less. What was the secret? The one word "simplicity" gives the answer. In an engineering sense, the most complex thing which had to be dealt with in all that time—other than the engines—were the gyro instruments, introduced around 1931-32, and these were not made by the aircraft company. No electronics, very little electrics—generators driven by windmills!—bomb release by wire pull-off and so on. The comparison with today is so striking that one is forced to ask the question "does the complexity of today's practice give us an adequate return or have we allowed the pendulum to swing too far?" Complexity in military aviation may be enforced by the nature of the requirement or by special circumstances outside the designer's control. But in civil aviation similar conditions are much less important and of course the whole effort is conditioned by economic considerations.

It occurred to me that it would be of interest to look at commercial transport aircraft over the past 30 or 40 years from the point of view of the overall advance in efficiency of the aircraft as a vehicle of transport, the contribution made by various parameters of design and effect of such developments judged against this vexed question of complexity. And it is vexed; how often one hears the older hands bemoaning the fact

*The Sixth R. K. Pierson Memorial Lecture delivered to the Weybridge Branch of the Society on 30th October 1957.

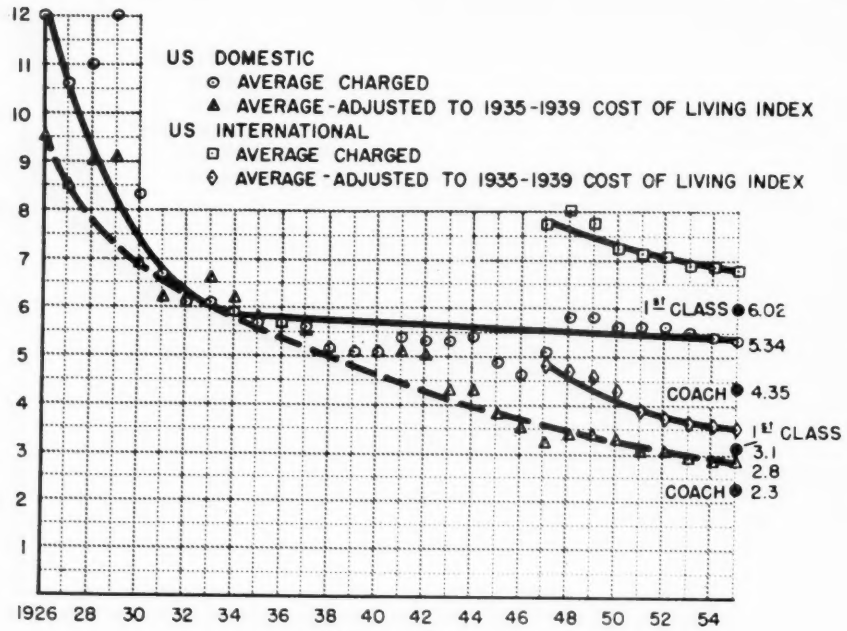

FIGURE 1. Air fares.

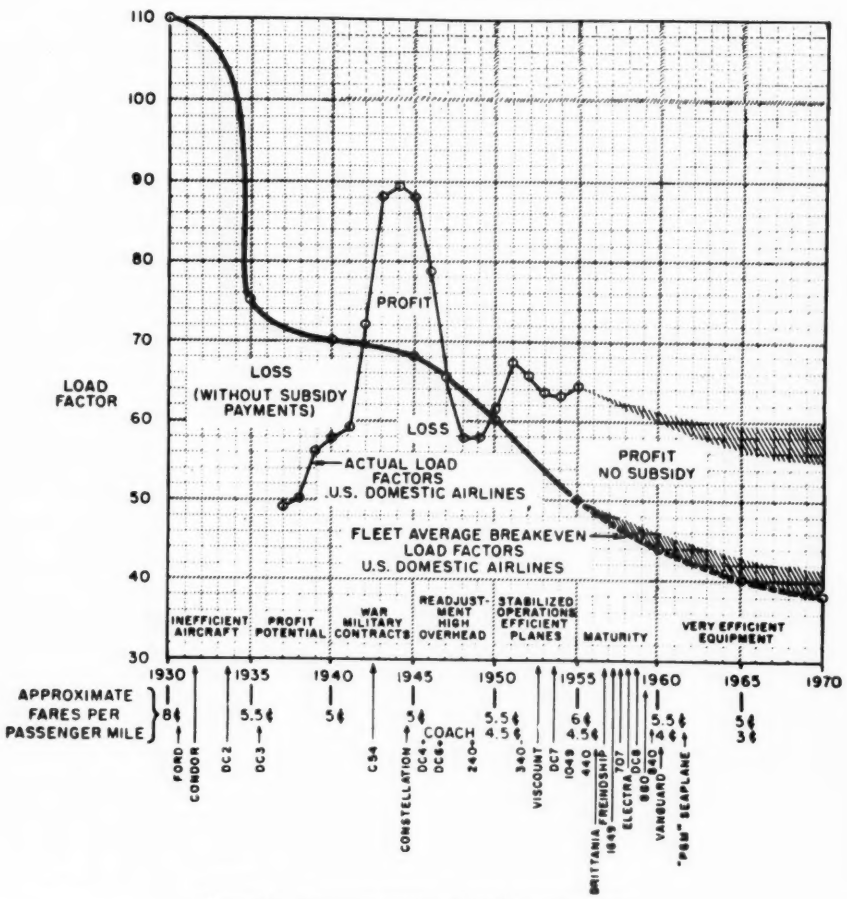

FIGURE 2. Revenue passenger load factors: trends.

that everything has become too complicated and we must get back to the earlier simplicity, I have said it myself many times. But the question is can we do this and still retain the advances which have been achieved? Of course one cannot expect a final answer to this in all its detail; one can only examine it in the broad and reach broadly-based conclusions. So the purpose of this paper is to take a backward look on the lines indicated.

LEGEND TO FIGURES

- BIPLANE— Fixed Undercarriage
- MONOPLANE— Fixed Undercarriage
- MONOPLANE— High Wing Retract. U/c.
- MONOPLANE— Low Wing Retract. U/c.
- MONOPLANE— High Wing Turbo-props
- MONOPLANE— Low Wing Turbo-props
- MONOPLANE— Turbo-jet
- FLYING BOATS

2. Direct Operating Costs

To get a global picture we can look at the variation of air fares over the years and also estimated direct operating costs, since the latter may be more immediately relevant to our purpose than fares, which contain elements unrelated to the efficiency of the aircraft as a vehicle. To make such pictures sensible, corrections have to be applied for the varying value of money over the years. Fig. 1 is taken from a paper by Dr. T. P. Wright[1], which came to my notice soon after I started working on material for this paper. Money values have been corrected to 1935-1939 standard. The continuing decrease in air fares in the U.S.A. is well shown; the decrease over the period of 29 years shown is about 3 : 1. Incidentally the trend is still downwards.

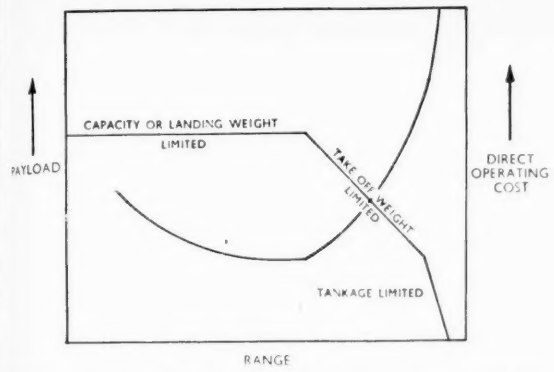

FIGURE 3. Typical payload and direct operating cost against range.

The fare can only be regarded as a true index of efficiency if it is correctly related to a profitable commercial operation and Fig. 2, again taken from Dr. Wright's paper, shows that before 1942 passenger operations in the U.S.A. were heavily subsidised to keep fares to a reasonable level—after 1950 the likelihood of profit seems to increase, the trend improving as far as the extrapolation has been carried. This picture is much more revealing than that of fares in indicating the progress made.

Estimates of direct operating costs for capacity payloads are now widely accepted as an important element in assessing the economics of air transport. The results are usually presented as a plot of cost (pence per ton mile) against stage distance, and result in a characteristic "U" shaped curve as shown in Fig. 3. The shape reflects, at short stages, increasing block speed as stage length increases from the very low values, the payload usually remaining constant, and at longer stages, decreasing payload, the weight being required for fuel as stage distance increases, hence increasing unit cost of transport. In the broad discussion throughout this paper, which in the main deals with trends, I have used a conventional value of payload, namely that which

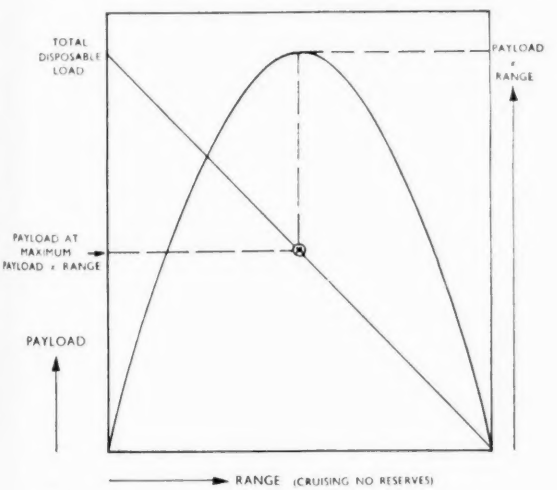

FIGURE 4. Payload for maximum payload × range.

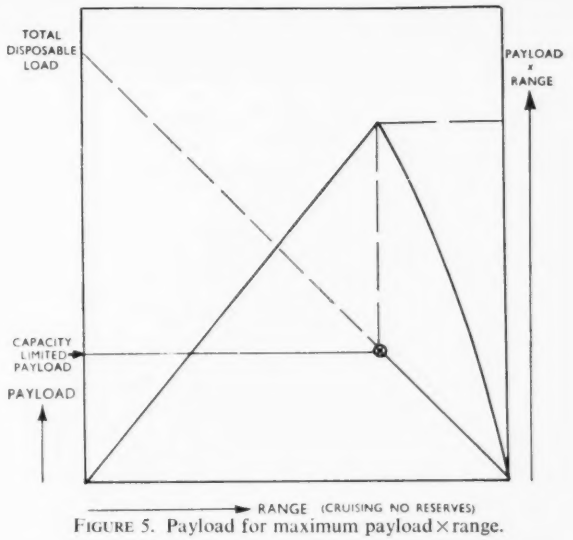

FIGURE 5. Payload for maximum payload × range.

makes the work capacity of the aircraft a maximum. This occurs either when payload is half the disposable load, as shown in Fig. 4, the product of payload × range being then a maximum *or* at the maximum value of payload, when it is limited by the capacity of the aircraft, as shown in Fig. 5. There is a simplification implied in the first alternative since fuel for climb, descent and diversion is neglected. Capacity payload has been taken as full seating plus passenger baggage and normal density freight in the available compartments, provided that the maximum payload specified by the manufacturer is not exceeded.

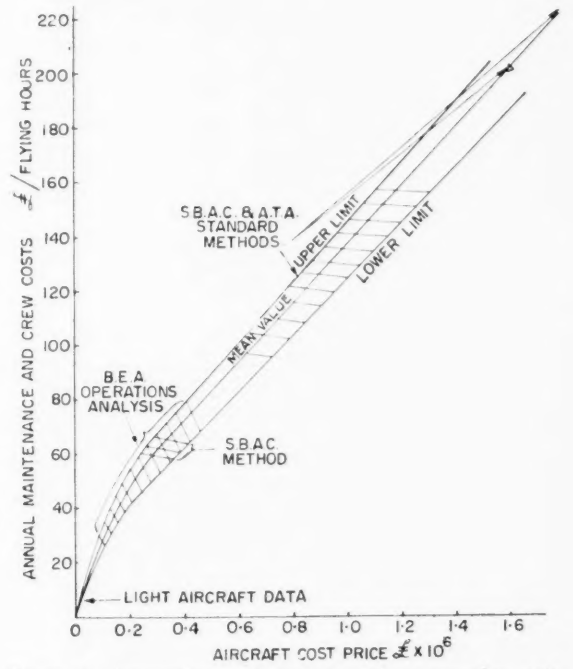

FIGURE 6. Assumptions and methods. Direct operating costs. An outline of the analysis of annual maintenance and crew costs.

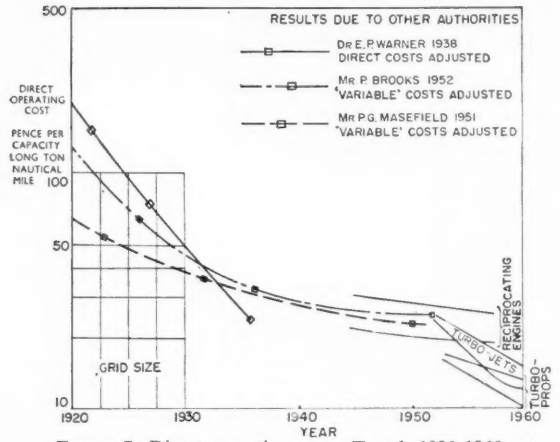

FIGURE 7. Direct operating costs. Trends 1920-1960.

Direct operating costs of some typical post-1945 aircraft have been placed on a common basis by a simplified method similar to that derived by F. Robertson[2]. Adjustment to the 1957 value of the pound is based on the similarity of the relative values of engineering wages and fuel prices. Annual maintenance and crew costs taken from many estimates, by standard methods and from published results from B.E.A. and other sources, are plotted against aircraft cost price as shown in Fig. 6. The scatter is within ± 10 per cent.

The resulting estimates of direct operating cost are in close agreement with known values obtained by the S.B.A.C. and other methods.

Data is increasingly scanty as one goes back into the past, but fortunately the ground has already been dealt with in a most authoritative way as Dr. Warner[3], Peter Masefield[4] and Peter Brooks[5] have all made estimates, shown in Fig. 7. The curves have been adjusted to bring them into line with our own information on estimates and published costs for the most recent aircraft they considered. Dr. Warner deals with six aircraft between 1920 and 1936 and Mr. Masefield and Mr. Brooks, between them, seven different aircraft

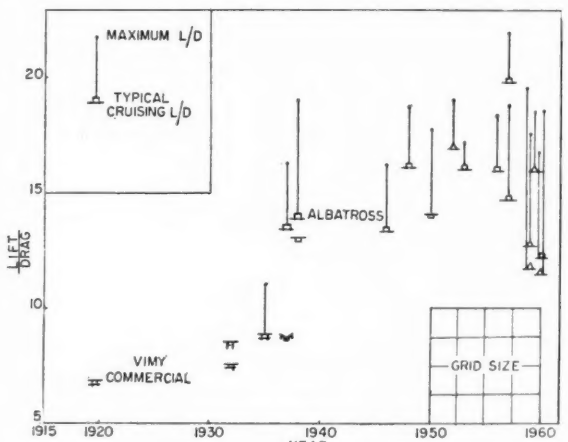

FIGURE 8. Cruising and maximum lift/drag ratios.

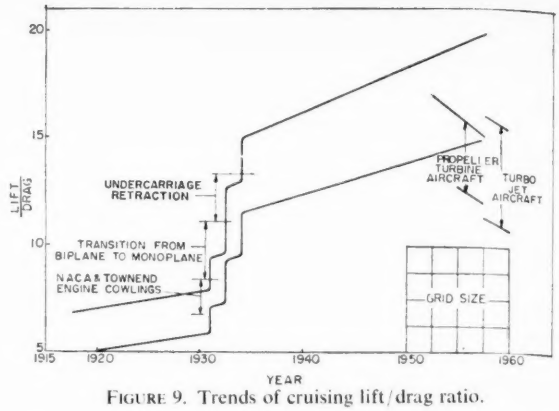

FIGURE 9. Trends of cruising lift/drag ratio.

between 1919 and 1951, so the ground is well covered. Over the 40 years, 1920-60, a reduction of the order of 13 to 1 in direct operating costs, seems to be feasible. The trend is still downwards, but there is a tendency to flatten out. A 3 to 1 reduction is shown between 1945 and 1960.

The results shown confirm what we all vaguely (or otherwise) felt; that we were making progress even judged by the most exacting standard of economy in operation which is the final arbiter in deciding the ultimate success of air transport, *i.e.* complexity has not so far "upset the applecart." What have been the main advances contributing to this somewhat surprising result—somewhat surprising in the light of the immense change in the level of complexity over the 30/40 year period under review?

3. Transport

All transport is concerned with moving people or goods or both from "A" to "B"—here to there. The consignee is primarily concerned with the completion of the operation, *i.e.* safe and punctual arrival in good condition and at a reasonable price; if he has consigned himself he is also interested in comfort and amenities. With these provisos, he is not really interested in the ironmongery and machinery of the vehicle. Obviously, from his angle, the magic carpet is good—provided the draught is also magicked away and the wine *en route*

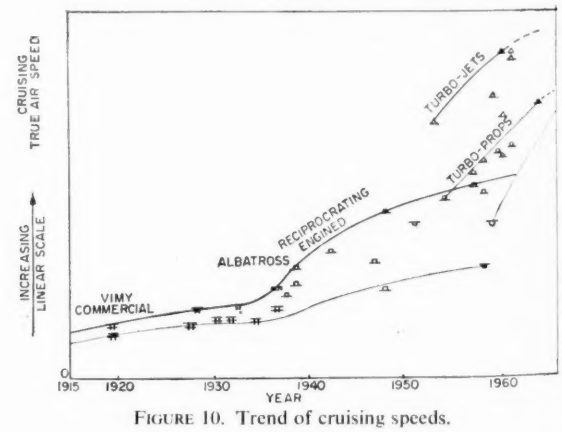

FIGURE 10. Trend of cruising speeds.

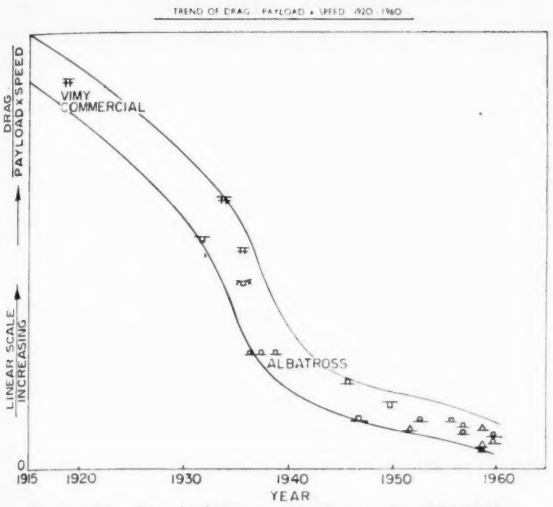

FIGURE 11. Trend of drag/payload × speed. 1920-1960.

is good—there is no fuss, the minimum of passenger processing and the red carpet all laid immediately on alighting. The consignor is not a bit interested in all the wonderful engineering of the aeroplane which surrounds his package or the seat in which he sits. Much as one dislikes saying so, the achievement of creating the vehicle is only incidental to its value to air transport, *i.e.* as the means to the end of getting passengers and goods from "A" to "B."

3.1. DRAG PER LB. OF PAYLOAD

A measure of the success of the aircraft as a vehicle from this rather idealistic standpoint is to take a parameter, such as drag in cruising flight per lb. of payload. This is a measure of how far the mundane departs from the magic. This parameter can be converted to a somewhat different form which may be more convenient for our purpose.

$$\frac{\text{Drag}}{\text{lb. of payload}} = \frac{1}{\dfrac{\text{Payload}}{\text{All-up Weight}} \times \dfrac{L}{D}} = \frac{1}{\dfrac{W_p}{W} \times \dfrac{L}{D}}$$

and this parameter will have its best value when W_p/W and L/D are at their highest. Taking L/D first and remembering that the lift is what is wanted for our air transport and the drag is the price we have to pay for the lift and the structure, and so on, which carries the lift to the load, Fig. 8 shows the way in which this factor has varied over the years.

A marked scatter is shown as one would expect, since a wide variety of aircraft are included, in size, power plant—jets, turbo-props, reciprocating engines—wing loading, standards of skill in engineering and structural design and stage of development. The data has been obtained from many sources, and so far as possible the results are accurate within reasonable limits; values of maximum L/D could be obtained only for the most recent aircraft. Cruising L/D for the biplanes were in the main deduced from cruising power, making use of the contemporary acceptable values of propeller efficiency where appropriate.

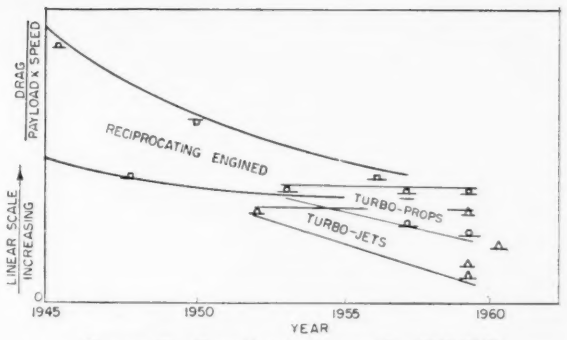

FIGURE 12. Drag/(payload × speed). 1945-1960.

The points for maximum L/D are of great interest since, except for one case, little advance is shown since the D.H. Albatross. I refer to this aircraft specifically for reasons which will appear later in the paper. The nearness of approach of the cruising condition to the maximum may be taken as a measure of success in matching airframe, engine and operating conditions. This point will be referred to later.

The marked improvement between 1930 and 1940 was, of course, due to many changes, notably from biplane to monoplane, introduction of retractable undercarriages, "clean" engine installations. Fig. 9 attempts to show what each was worth, although the results must not be taken too precisely, because the estimates obviously involve simplifying assumptions. Note that each one of the steps involved increased complexity, but *in toto* they accounted for about 60 per cent of the improvement from 1930 to the present day.

Concurrently with these improvements, speed was steadily rising, but part of this must be attributed to higher stalling speeds and in consequence the need for runways of steadily increasing length grew. In fact the runway was born out of the passenger air transport need which brought about the change to nosewheels and the necessity for smooth take-off and landing surfaces. The trend of design has confirmed the transition to nosewheel, but the outpouring of concrete seems to be a "complexity" which has gone too far. A powerful plea for improvement was put forward by

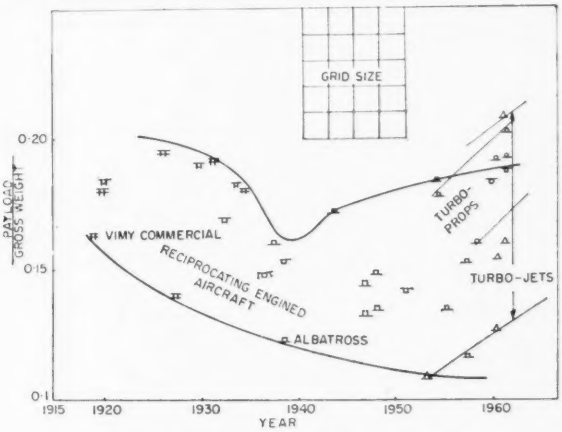

FIGURE 13. Trend of payload/gross weight.

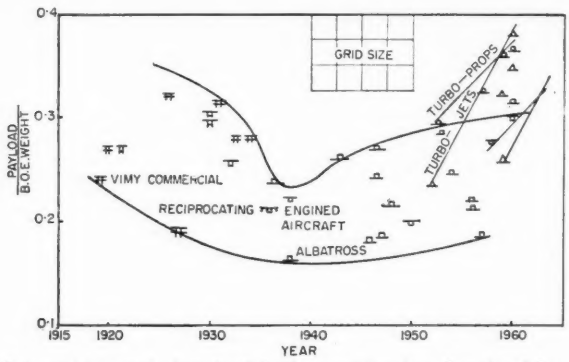

FIGURE 14. Trend of payload/basic operational equipped weight.

Sir Frederick Handley Page[6] in his Bleriot Lecture of 1950.

This steady trend of increasing speed is shown in Fig. 10 which brings out the value of the aerodynamic cleanness of the "Albatross" and the spectacular rate of advance due to the use of turbine engines. The effect of this trend on the very simple drag/payload criterion is shown in Figs. 11 and 12, which compare drag with the rate of doing transport work. An improvement of the order of 14 to 1 is obtained over the whole period which includes a 2 to 1 advance since 1945.

3.2. PAYLOAD/ALL-UP WEIGHT

I mentioned earlier the factor of payload/all-up weight which is worth examining in building up the picture of how advancements have come about over the years. This is shown in Fig. 13.

The variation covers a wide scatter; in the broad one sees quite clearly the penalty associated with increasing engineering complexity, biplane to monoplane, retracting undercarriage, tail wheel to nosewheel, higher aspect ratio wings, increased landing speeds and so on. However, the scatter is in the main accounted for by the varying range requirements. There is, however, one point of particular interest—that for the D.H. Albatross. On the basis of Richards' criterion[7] for profile drag, this was an exceptionally "clean" aircraft,

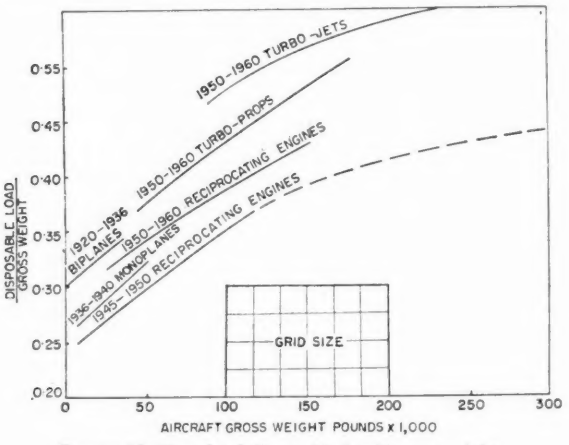

FIGURE 15. Trends of disposable load/gross weight.

in fact well in advance of its day in this respect. In addition, it had a monoplane wing of unusually high aspect ratio, its aerodynamic cleanness in flight being thus exceptionally high as seen earlier. However, one must assume that these results were obtained with an undue expenditure of weight leading to the low value of W_p/W shown; moreover, the war prevented the development of the aircraft to improve it in these respects. This picture, which apparently shows such low values of the index for the most modern aircraft, obviously over-simplifies things. In Fig. 14 the ratio of payload to basic operational equipped weight is shown, and this is nearer the true position, the gross effects of range being eliminated. This clearly shows the advances made during and since the Second World War, attributable to a steady improvement in materials —airframe, power plant and equipment; improved aerodynamics, maybe supported by a vast outpouring of concrete to create the runways of the world, a steady advance in power plant output per lb. of installed weight with, of course, a rapid improvement of this factor with the coming of the gas turbine. In every case I think it would be true to say that the advance has been accompanied by increasing complexity in design, in engineering, and in production of materials and their fabrication into the aircraft parts.

3.3. DISPOSABLE LOAD/ALL-UP WEIGHT

A more realistic factor than those mentioned is the ratio of disposable load to all-up weight which General du Merle[8] referred to in his Bleriot Lecture of 1953. He showed very clearly, in a most interesting treatment, its dominating influence on all-up weight at long ranges. In Fig. 15 we have perforce discriminated between biplanes, monoplanes, and various types of power plant, and presented the picture in a series of curves against all-up weight. A steady advance is shown in the carrying capacity of our "ironmongery"—the carrying capacity which determines the total transport work within the capability of the aircraft in one stride. Clearly we are

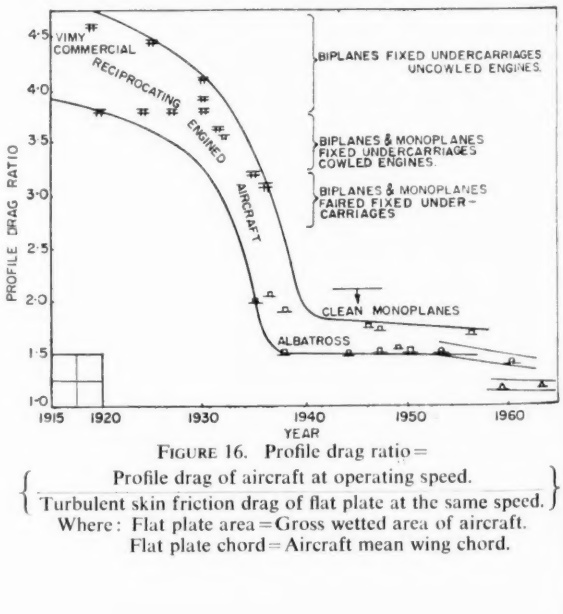

FIGURE 16. Profile drag ratio =

$$\left\{\frac{\text{Profile drag of aircraft at operating speed.}}{\text{Turbulent skin friction drag of flat plate at the same speed.}}\right\}$$

Where: Flat plate area = Gross wetted area of aircraft.
Flat plate chord = Aircraft mean wing chord.

getting something for our money, since the ratio has moved from about 0·3 just before the war to about 0·5 in 1960. But I think the true picture of overall advance is best shown in the increased rate of doing transport work which will be referred to later.

So far then, from our examination of the factors contributing to the very simple criterion of drag/lb. of payload, we can see advances over the years which will help to compensate for increased complexity. In fact the simple presentation of ratio of payload to all-up weight showed little change between the early years of the period and today. It is in the factor of drag then that we have made the advance; this is shown most graphically in Fig. 16 following the treatment used by Professor Richards in his lecture on "Aerodynamic Cleanness"[7], although some further points have been added, including that for the D.H. Albatross, previously referred to. The other point to notice is the very low profile drag of the jets, a significant bonus from the use of this class of power plant.

In the search for low cruising drag there has been a steady trend to higher aspect ratios with a sharp reduction recently with the coming of high speed jet aircraft, as shown in Fig. 17. This latter presumably is a compromise made necessary by the aerodynamic and structural developments to avoid the early onset of wave drag and to deal with aeroelastic problems, and made feasible by the sharp drop in profile drag referred to earlier. The achievement of such high aspect ratios has come by the acceptance of increasing demands on metallurgical and engineering and aerodynamical knowledge and skills. The measure of the technical advance, to be reckoned against the steadily rising level of technology and effort needed, is shown in the steady reduction of drag per lb. of payload taking the drag corresponding to cruise reduced to the standard speed of 100 ft./sec.

We have most certainly wrapped cleaner aeroplanes round our packages of payload; overall there is an improvement of the order of 40 to 1 and compared with the average value just before the war the advance promised in 1960 is about 7 to 1.

4. Rate and Range of Air Transport

In this very simple approach to the assessment of our advance over the years judged against the increasing complexity, we have so far left out of account two highly important factors in the transport problem; the first is the rate of doing transport work and the second is the range, the distance of carriage, point to point. In his paper "European Air Transport Economics"[9], Stephen Wheatcroft describes the product of capacity payload times cruising speed as the most important index in air transport. Payload enters in directly, drag only indirectly. It is the index of the potential revenue-earning rate of aircraft in use, and hence one of the yard-sticks of success of the aircraft industry. Another yard-stick is range, and the two are clearly inter-related. Fig. 18 shows a parameter, which can be taken as a measure of efficiency, *i.e.* rate of transport work per lb. of all-up weight; a tenfold advance over the period is shown. The spectacular advance which the gas turbine has

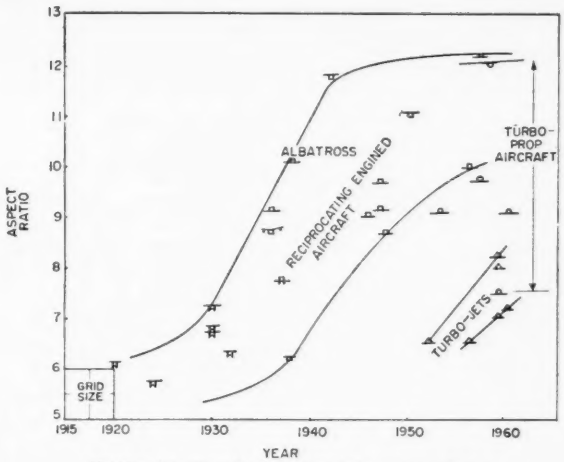

FIGURE 17. Trend of aspect ratio—monoplanes.

made possible is the most notable feature, but it is curious that over the whole period before this there are no sudden changes such as one saw in examining the other factors. As we all know, the advances were obtained by hard slogging and it now seems clear that the piston-engined aircraft was reaching the limit of its useful achievement.

In Robertson's[2] formula for the simplified estimates of direct operating costs—and the methods used in preparing the data presented in this lecture give similar results—the cost is the sum of two terms, the first depending on the inverse of rate of transport work per lb. of basic operational equipped weight and the second on the inverse of the total transport work per lb. of fuel carried. The index of efficiency I propose does not seem to line up with this and to throw light on the matter, D. W. Wall, who has been helping me in the preparation of data, suggested plotting the reciprocal of minimum direct operating cost, shown earlier, against the index of efficiency shown in Fig. 18. The most striking thing in this Fig. 19 is the lack of scatter from a mean line for all the aircraft fitted with propellers, reciprocating and turbine-engined. As might have been

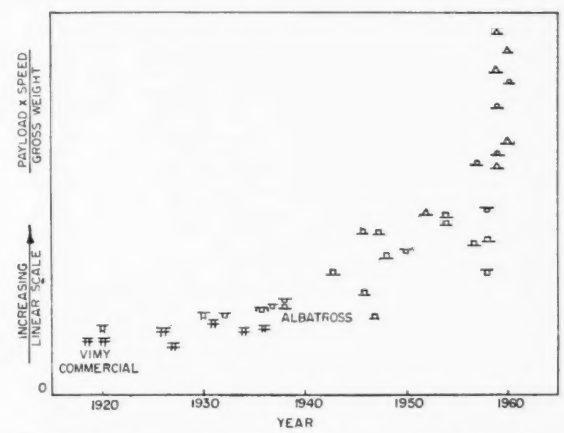

FIGURE 18. Rate of transport factor. Payload × speed/gross weight. Showing trends.

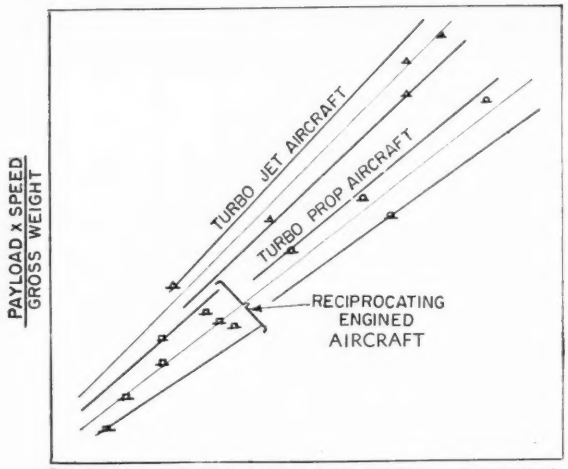
PAYLOAD x SPEED / GROSS WEIGHT
TURBO JET AIRCRAFT
TURBO PROP AIRCRAFT
RECIPROCATING ENGINED AIRCRAFT
RECIPROCAL OF DIRECT OPERATING COSTS → INCREASING

FIGURE 19. Relationship between the two indices of transport efficiency.

expected, jet-driven aircraft depart from the others; again there is little scatter—long and short range aircraft are included among the points shown—and a single line through the origin forms a good mean. The interpretation of the two distinct mean lines is that the proposed index applies only to comparisons of aircraft within the two groups, jet or propeller-driven; it cannot be used for comparison between jet and propeller-driven aircraft. Presumably this distinction reflects in part the lower efficiency of the jets in converting energy in the fuel to thrust power. It is an interesting form of presenting the results; apparently the amount of transport done per unit cost is directly proportional to the maximum rate of transport work per unit of all-up weight.

The difference between the jets and the others is made up partly due to first cost and partly due to fuel cost. First cost, reduced to a common value of currency, is shown in Fig. 20. Information has been taken from Sir Richard Fairey's Wilbur Wright Memorial Lecture of 1950[10] for the pre-1940 part of

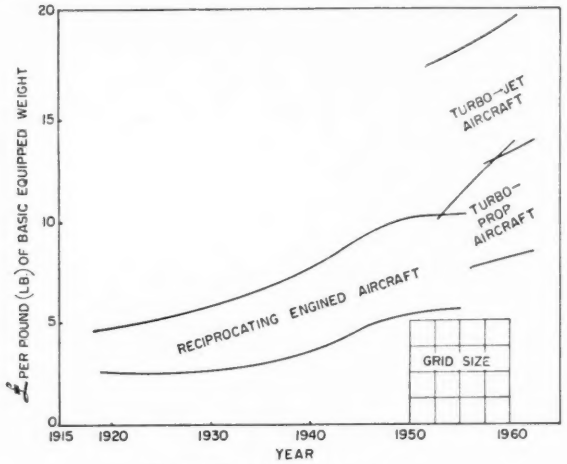

FIGURE 20. Aircraft cost price.

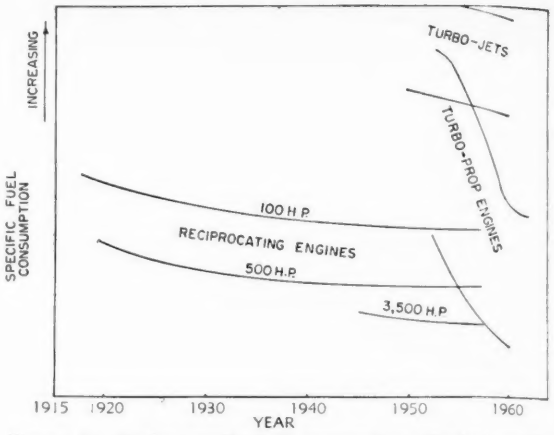

FIGURE 21. Engine specific fuel consumption. Typical cruising conditions. Turbo-jet equivalent at 450 KTS allowance for propeller efficiency.

the period, his values being converted to 1957 values by comparison with known values of a number of the more recent aircraft he discussed. The overall effect on cost of increasing complexity is well shown, as also is the greater cost of the jet aircraft. This is rather puzzling at first, since one thinks of jet propulsion as having brought a material simplification. This is, of course, only superficially true; the complexity is there, although maybe hidden. The increased speeds made possible by the jet engine are approaching $M=1$, involving swept surfaces of low thickness/chord ratio, very smooth, stiff coverings, power operated controls and new levels of structural rigidity to meet the problems of aeroelasticity. Every aspect of the work requires higher standards of achievement—the materials, the basic and detail design, the engineering, the workmanship, the flying; and this is true for all that is brought together to make the aircraft an operational entity—airframe, engines, systems, controls, equipment of all kinds. The accent is on engineering of the highest class and it is costly. Moreover, there is a size effect; jet transport aircraft are in general bigger than their propeller counterparts for a given payload/range characteristic.

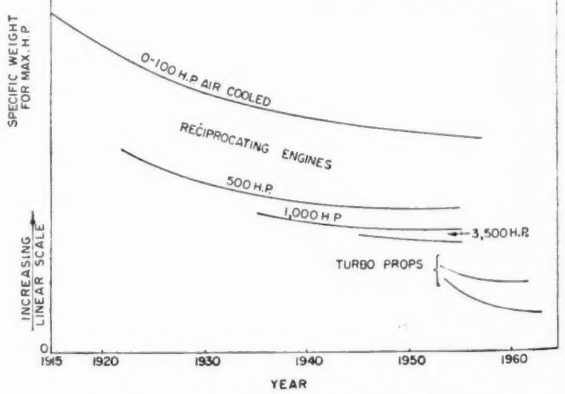

FIGURE 22. Engine specific weight at maximum power.

5. Power Plant

The major factor remaining for discussion is the power plant. du Merle[8] has shown how fundamentally the efficiency of the power plant influences the size of aircraft for a given payload and range, assuming certain standards of aerodynamic and structural efficiency. Correspondingly, for given airframe values range is, of course, directly related to power plant efficiency. The factor which one thinks of first is the specific fuel consumption; the very great improvement over the years is manifest in Fig. 21 as also is the spectacular rate of advance in the gas turbines. The scatter indicated is of course explained by the varying stages of development of the available engines. The pleasant notion of applying a propeller efficiency to the nominal figure of jet thrust horse power is, of course, for comparative purposes. Engine specific weight is shown in Fig. 22, and again the gas turbine is outstanding. Propeller efficiencies have also steadily improved; over the years the factor of propeller efficiency multiplied by the reciprocal of specific fuel consumption had improved by 1·7:1 for reciprocating engines and is still improving for turbo-props. This seems a fair return for the mounting level of technical effort in research and development.

6. Transport Efficiency Factor

The overall progress is reflected in the transport efficiency factor; and in the increase of usable range over the years. Not only have we advanced in distance as an absolute value, but of course speeds have increased as well.

The results of this survey seem to show that the "game is worth the candle," since economic advantage attends the steadily increasing complexity of the product. Implicit are two assumptions, firstly that the product continues to meet the existing standards of reliability in use and secondly that the utilisation is unchanged. There is, I think, a proviso that the present trend towards longer and longer runways which accompanies the strictly aircraft advances is unacceptable and is likely to prove an increasing handicap to the economic use of air transport if allowed to continue.

If we take the maximum rate of doing transport work per unit weight of aircraft fully laden as an approximate index of efficiency, then the experience so far is that the reduction in drag has been the dominant factor in the improvement over the years. It is an improvement served by all other advances in structures, engines, pressurisation, even runways. Hence the theme of B. M. Jones (now Sir Melville) in his paper on "The Streamline Aeroplane"[11] is completely endorsed out of practical experience.

7. Conclusions

As a final word I would invite your attention to the comparison in the shapes of the two curves of efficiency factor and first cost (Figs. 18 and 20). The similarity is striking; in fact the relation between these two quantities is practically linear. One may, I think, legitimately deduce that we have made no major breakthrough in the aeronautical field during the past 40 years so far as regards air transport; we have "kept up with the Joneses" and no more, and that's been pretty hard going. But surely it is significant that we have made no major advance in profile drag since 1938-40, the days of the "Albatross." Is this not then our most fruitful field of research and development for transport aircraft and not the supersonic $M=3$ aircraft which, if ever built, will serve only highly specialised routes and not the general field of air transport?

In this sense then complexity—apparently needed to keep advancing—is misleading; we obviously cannot return to the old simplicity, but new knowledge may be revealing simpler ways of making progress. Curiously, I find that in an entirely different approach I have reached a similar conclusion to that of Professor Richards in his lecture referred to earlier. I believe myself to be in good company.

ACKNOWLEDGMENTS

May I make most grateful acknowledgments to all who have given me so much help in preparing this paper, in providing data, in discussion, in making slides and so on, especially to Mr. D. W. Wall who has carried the main burden of collection and getting into shape for presentation.

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Definitions to be used in the Description and Analysis of Drag

Report of the Definitions Panel

(Although already published by Her Majesty's Stationery Office (as A.R.C. Current Paper No. 369) this report and the one which follows on p. 801 (A.R.C. Current Paper No. 368) are considered to be of such general interest that they are published here at the suggestion of the Aeronautical Research Council, so that they may have a more permanent form of publication and a wider circulation.—Ed.)

SUMMARY:—Terms used in the description and analysis of the external drag of a body (with or without internal flow) are considered, and definitions suggested for the various components of the drag. Care has been taken to ensure that the proposed terms are consistent with those used in the Panel's report on thrust[2].

1. Introduction

With the attainment of supersonic flight, the speed range through which the drag of an aircraft must be measured or estimated has increased considerably. Terms in common use for describing low speed characteristics have had their use extended to supersonic flight speeds and sometimes confusion and ambiguity have resulted. In its present form the British Standard Glossary of Aeronautical Terms[1] does not resolve the difficulties satisfactorily and the ever-increasing demand for data on drag at high speeds has emphasised the need for a set of precise terms, of wide application, which would enable a logical analysis of the drag to be made.

Early attempts to meet this need were made by Warren in two unpublished papers. These were discussed by the Performance Sub-Committee of the Aeronautical Research Council in 1953, when it was agreed that the subject required further consideration. At the Sub-Committee's request the Definitions Panel was set up to consider the definitions of terms used in describing and analysing external drag, and also the problems which occur in defining the thrust and internal drag of a ducted body. A Report[2] by the Panel on the latter subject appeared in May, 1954; the present Report deals with the terms used in the description and analysis of external drag. Both these reports refer only to the case where the thrust acts in the direction of the undisturbed stream. *i.e.* along the line of flight.

The Panel, which first met in May, 1953, was composed of the following members who were nominated by two Sub-Committees of the Aeronautical Research Council: —

Nominated by the Performance Sub-Committee

Professor W. A. Mair	(*Chairman*)
Mr. D. W. Bottle	(A. & A.E.E.)
Dr. R. C. Pankhurst	(N.P.L.)
Mr. T. V. Somerville	(R.A.E.)
Mr. C. O. Vernon	(S.B.A.C.)
Mr. C. H. E. Warren	(R.A.E.)
Mr. E. W. E. Rogers	(N.P.L.) (*Secretary*)

Nominated by the Engine Aerodynamics Sub-Committee

Mr. S. Gray	(M.O.S.)
Mr. H. Pearson	(S.B.A.C.)
Dr. J. Seddon	(R.A.E.)

2. Statement of the Problem

In the present Report the body, which may possess an internal duct, is assumed to be immersed in a steady uniform stream of fluid which is both viscous and compressible; gravitational forces are ignored. Drag is positive if it acts in a downstream direction.

The fluid may conveniently be divided into that part which flows outside the body (*External Flow*)* and that which flows through the body (*Internal Flow*). The surfaces bounding the internal and external flows will be called the *Internal* and *External Surfaces*, and the drags associated with the internal and external flows, the internal and external drags†. It should be noted that the internal and external drags are not necessarily manifested as stresses which appear only on the corresponding surfaces of the body but are related to the internal and external flows.

To analyse the external drag, it is necessary to assume that no mixing takes place between the internal and external flows, both ahead of and behind the body. Thus ahead of the body the flows are considered to be separated from each other by the surface of the *Pre-Entry Streamtube*. Behind the body, where turbulent

Received February 1958.

*Terms which are italicised are defined in the Appendix.

†Internal drag (which is discussed in Ref. 2) may become negative if heat is added to the internal flow and the definitions set out in this Reference are then appropriate.

mixing between the internal and external flows would normally take place, it is convenient to postulate the existence of a similar dividing stream-surface, the *Equivalent Post-Exit Streamtube*. It is further assumed that no shearing stress occurs between the internal and external flows along these streamtubes.

While the analysis requires the assumption that the internal and external flows do not mix, there is no restriction on mixing within the external flow itself; indeed it is, in general, only because of mixing that at large distances downstream from the body the static pressure approaches that of the undisturbed stream. Thus to correspond with the definition of thrust given in Reference 2, the *Total Drag* associated with the external flow is given by the rate of decrease of momentum of the external flow in a direction parallel to the undisturbed stream, this decrease being calculated between stations at infinite distances upstream and downstream of the body.

The most convenient method of analysing the total drag is to some extent dependent on the type of problem being considered. In general, two systems of analysis are required. The first is made in terms of what have been called "drag concepts" in the present Report; these are the components of drag obtained by considering how the drag forces arise and are experienced by the fluid boundaries. The second analysis is made in terms useful for the estimation of drag.

3. Drag Concepts

It is convenient to resolve the force acting on an element of the body surface into two components, normal and tangential to the surface. The normal and tangential forces may in turn be resolved to give components in the downstream direction; the resulting drag forces can be called *Normal-Pressure Drag* and *Surface-Friction Drag* respectively. Should shorter names be required, the use of Pressure Drag and Friction Drag is recommended. The sum of the Normal-Pressure and Surface-Friction Drags is the Total Drag.

For a body with no trailing vorticity, in an ideal fluid and in the absence of shock waves, the normal-pressure drag is zero (d'Alembert's paradox). For a real fluid, however, because of energy dissipation within the boundary layer, a drag force is experienced by the body and this may be called *Boundary Layer Drag*. Boundary layer drag is experienced by the body partly as surface friction and partly as a change in the distribution of normal pressure; the latter may be called the *Boundary Layer Normal-Pressure Drag*. Further, when shock waves are present, an additional component of drag arises from the energy dissipated in the shock waves; this component may be called *Wave Drag*.

The generation of lift by either the whole body or some part of it will, in general, alter the magnitudes of the boundary layer normal-pressure drag and wave drag and in addition will give rise to a trailing-vortex system. The kinetic energy that is being continually added to the trailing-vortex system is derived from work done against *Trailing-Vortex Drag**, which appears on the body as the third component of the normal-pressure drag. If a shorter name is required, the term Vortex Drag is suggested for this quantity.

It should be emphasised that these drag concepts are not independent of one another. Thus, for example, the change of pressure distribution caused by the presence of the boundary layer leads to a change in the shock-wave system, so that a part of the boundary layer normal-pressure drag may appear as a contribution to the wave drag. Again, the energy dissipation associated with regions of interaction between shock waves and boundary layers cannot be separated into wave drag and boundary layer drag except in an arbitrary way. It must also be noted that a change in any one drag component due to some flow change (*e.g.* a movement of the transition point) will, in general, be accompanied by changes in the other drag components.

The transfer of heat between the body and the external flow will lead to a change of total temperature within a narrow layer of fluid adjacent to the body surface (the thermal boundary layer) and there will in general be a corresponding change in external drag. Indeed in certain circumstances the total drag may become negative, *i.e.* there may be a thrust, since the transfer of heat between the body and fluid may constitute a form of heat engine. Quite apart from this, the heat flow between the body and the fluid may have large effects on the stability of the boundary layer, causing changes in drag. However, no new drag concepts are required in such cases as the associated drag changes appear as changes in the various drag components already described.

When the drag concepts already discussed are applied to a ducted body, special consideration of the normal-pressure drag is required. From the definition of total drag given in Section 2, it is found that this consists not only of the force component parallel to the stream arising from the pressure and friction forces acting on the external surfaces of the duct, but also of the components arising from the pressures on the outsides of the pre-entry and equivalent post-exit streamtubes. These drag forces on the outsides of the pre-entry and equivalent post-exit stream tubes are, of course, equal and opposite to the pre-entry and post-exist thrusts discussed in Ref. 2. They are not drags in the dissipative sense and are not associated with any increase of entropy; they arise solely from the division of the forces on the ducted body into components due to the internal and external flows. The normal-pressure drag of a ducted body can therefore be regarded as a drag component arising from the normal pressures on the fluid boundary extending from infinity upstream to infinity downstream, part of which is the actual surface of the body.

*This quantity is frequently referred to as the "induced drag," particularly for low-speed flows, but it is recommended that the term "induced drag" should be avoided as it is at present used with more than one meaning. (*See also* the discussion of Lift-Dependent Drag on page 800.)

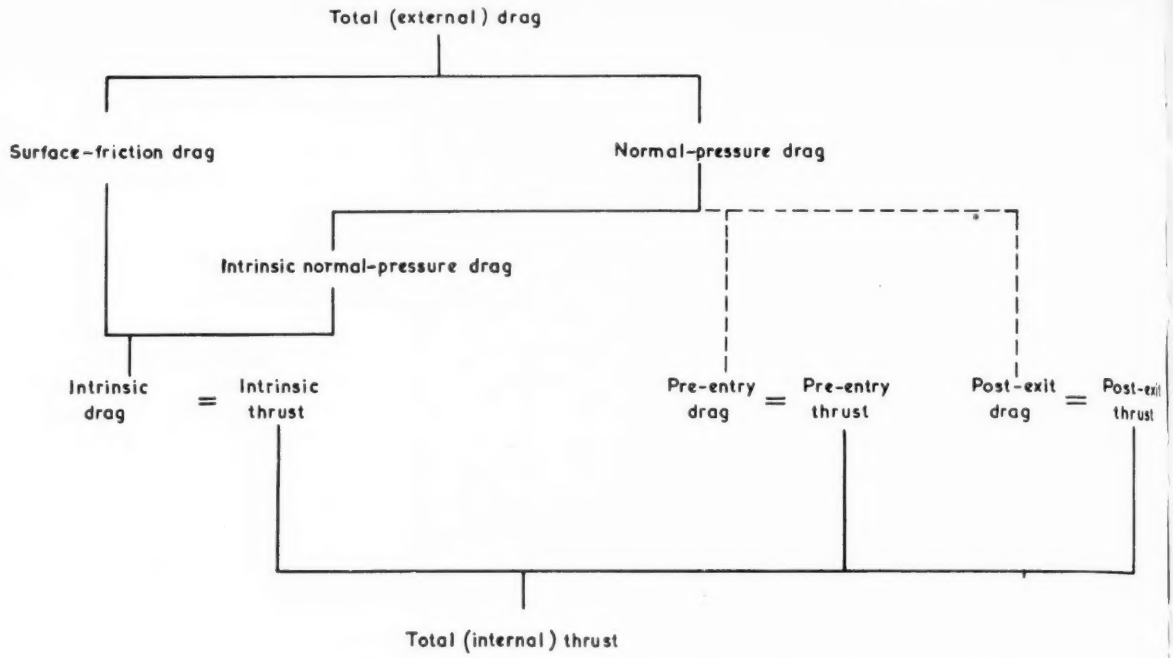

FIGURE 1(*a*). Diagram showing balance between thrust and drag for a ducted body in level flight with zero acceleration.

It is realised that this extension of the term "normal-pressure drag" to the case of a body with a duct is novel and that the normal pressure drag associated only with the external surfaces of the body is at present that commonly called "normal-pressure drag." The Panel feels, however, that the proposed definition for this quantity is logical and consistent with the terminology of Ref. 2 and to illustrate this point, the relation between the thrust and drag analyses is shown diagrammatically in Fig. 1(*a*), and is discussed further.

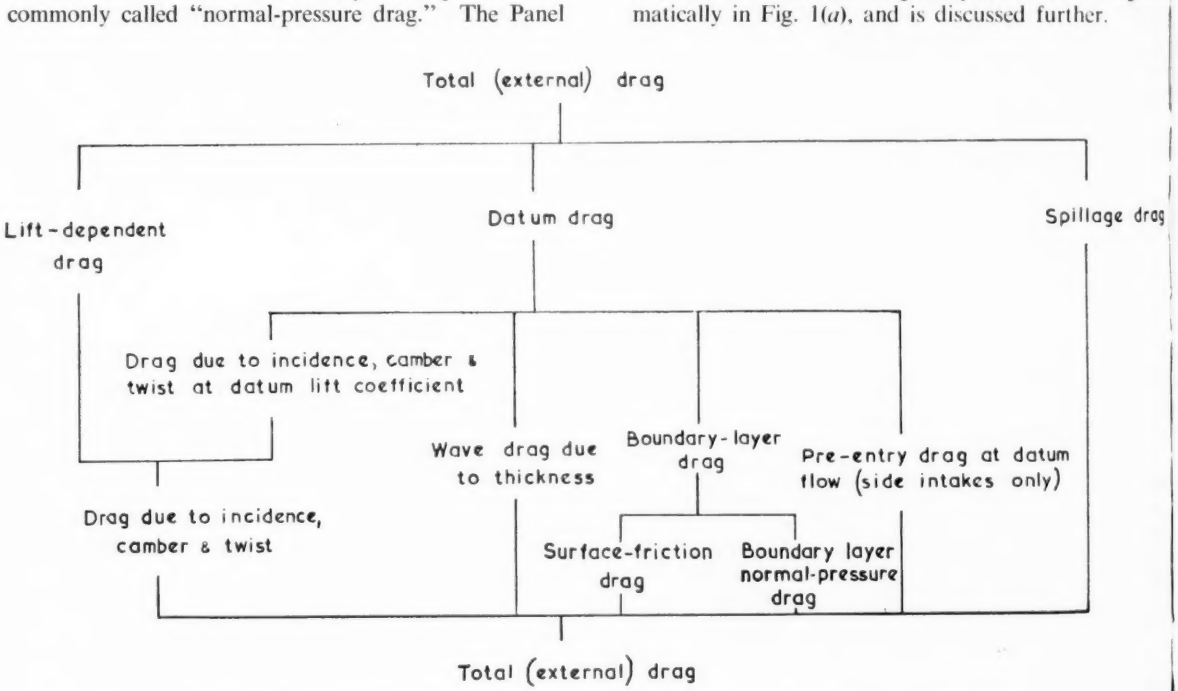
Total (external) drag
Lift-dependent drag
Datum drag
Spillage drag
Drag due to incidence, camber & twist at datum lift coefficient
Wave drag due to thickness
Boundary-layer drag
Pre-entry drag at datum flow (side intakes only)
Drag due to incidence, camber & twist
Surface-friction drag
Boundary layer normal-pressure drag
Total (external) drag

FIGURE 1(*b*). Analysis of total drag in terms useful in drag estimation (assuming independence of spillage drag, lift-dependent drag and boundary layer drag).

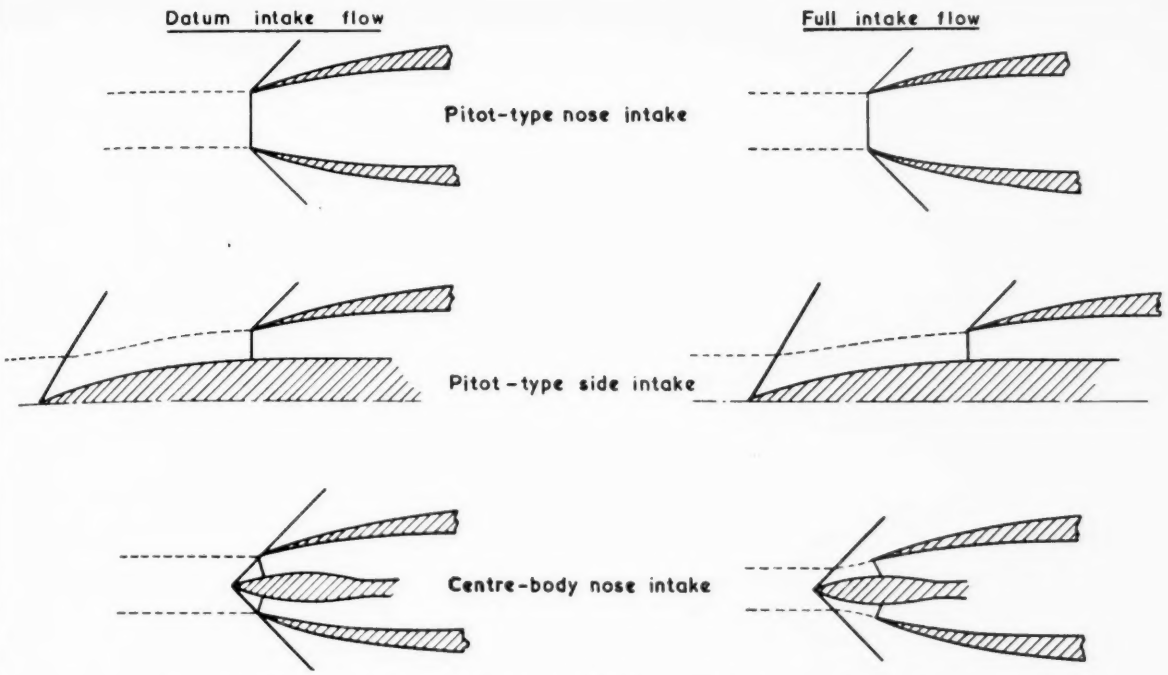

FIGURE 2. Diagrams of datum intake flow and full intake flow for various types of intake.

4. Terms Useful in Drag Estimation

The drag components listed in Section 3, although useful in illustrating the nature of the drag, are often unsuitable for use in estimating drag. It has already been mentioned that when calculating the drag of a ducted body it is desirable to introduce fictitious drag components obtained from considering the forces on the surfaces of the pre-entry and post-exit streamtubes; these can be called the *Pre-Entry Drag* and the *Post-Exit Drag* and are indicated by broken lines in Fig.1(*a*). It may be convenient however to have a name for the drag associated with the pressure distribution actually observed or estimated on the body's external surfaces and, by analogy[2] with the corresponding thrust component, it may be called *Intrinsic Normal-Pressure Drag*. The sum of this and the pre-entry and post-exit drags will be equal to the normal-pressure drag for the ducted body, as defined in this Report. In Ref. 2 the intrinsic thrust includes the surface friction on the internal surface of the ducted body; the analogous quantity for the external drag, if required, could be called Intrinsic Drag and would be the sum of the intrinsic normal-pressure drag and the surface-friction drag (*see* Fig. 1(*a*)).

Since the drag associated with the internal flow will in general vary with the flow into the body, it is necessary to specify a datum value for this (*Datum Intake Flow*), defined as the flow obtained when the boundary of the pre-entry stream tube is unaffected by the presence of the intake. (It may however be affected by the presence of other parts of the aircraft as, for example, with side intakes, *see* Fig. 2.) Thus for a Pitot-type nose intake operating at datum intake flow, the cross-sectional area of the pre-entry stream tube at infinity upstream is equal to the intake entry area measured normal to the undisturbed stream. For a Pitot-type intake at the side of a body, the Mach number at the entry will be different from the free-stream value because of the presence of the body; for this case only, there exists a *Pre-Entry Drag at Datum Flow**.

Spillage occurs when the intake operates at a mass flow other than the datum intake flow. When the change of mass flow is caused by the presence of a pre-entry compression body in the intake, *Full Intake Flow* is said to occur if the pre-entry stream tube, although modified by the pre-entry body, is unaffected by the cowl (Fig. 2). Full intake flow is less than datum intake flow by an amount called the *Basic Spillage*. For an intake without a pre-entry compression body the basic spillage is zero, the full intake flow being identical with the datum intake flow. When the actual flow is smaller than the full intake flow, the difference between these two quantities is called the *Incremental Spillage*.

Spillage of the air approaching the intake causes an alteration of the normal-pressure distribution and surface friction on the body's external surfaces. Thus associated with the three conditions of spillage are *Spillage Drag*, *Basic Spillage Drag* and *Incremental Spillage Drag*. These terms are defined in the Appendix.

*Some care is required in analysing the flow into a side intake since presumably the pressure and friction forces on the body surfaces upstream of the entry are associated with the internal and not the external flow. (*See also* Appendix IV of Ref. 2.)

Thus changes in total drag caused by alterations in the internal flow can be allowed for in terms of spillage; similarly drag changes caused by changes in the lift of the body from some *Datum Lift Coefficient* can be regarded as *Lift-Dependent Drag*. In the most general case, the spillage drag will vary with the lift coefficient, and the lift-dependent drag will depend on the internal flow. However, it is usually assumed that the spillage drag and lift-dependent drag are in fact independent of one another, and that lift-dependent drag is measured at datum intake flow. The *Datum Drag* may be defined as the value obtained at both datum intake flow and datum lift coefficient.

The value chosen for the datum lift coefficient is to some extent arbitrary, but it is recommended that it is defined as the lift coefficient at which, for given Mach and Reynolds numbers, the drag coefficient is a minimum. Thus if the body is asymmetric the datum lift coefficient is not, in general, zero. In the past, the drag at zero lift has often been called "profile drag," although this term has also been used to describe the total drag of a two-dimensional aerofoil, or the drag due to the wing of an aircraft at either the minimum drag or zero-lift condition. To avoid such ambiguity, the Panel feels that the term "profile drag" should be avoided and that in future the *concept* of *datum drag* should be used instead. The drag increment which accompanies an increase in the lift of the body has often been called "induced drag." Unfortunately, this term also has alternative meanings, such as the increase in drag from the zero-lift condition, or the drag due solely to the trailing-vortex system. Because of this ambiguity, the Panel recommends that the name "induced drag" should not now be used and the term *lift-dependent drag** should be employed.

It is also often convenient to assume that the drag due to viscous effects is independent of both the internal flow through the body and the lift. Thus the *Boundary Layer Drag* may be regarded as one component of the datum drag, which also includes the *Drag due to Incidence, Camber and Twist at Datum Lift Coefficient* and the *Wave Drag due to Thickness.*

The foregoing analysis is shown diagrammatically in Fig. 1(*b*).

The Panel appreciates that there exist other and perhaps equally acceptable analyses of drag which are useful in certain aspects of performance estimation; it is felt, however, that the one presented here is of wide application and merits consideration.

*It will often be convenient to assume a relation of the form

$$C_{D_L} = k(C_L - C_{L_0})^n$$

where C_{D_L} is the lift-independent drag coefficient, C_{L_0} and C_L are the datum and actual lift coefficients and k and n are constants (usually $n=2$). Strictly C_{D_L} depends on an increment of lift from the datum value C_{L_0} and not on the total lift, and hence ought to be called the "lift-increment dependent drag." The Panel feels, however, that it may be more convenient to use the shorter term "*lift dependent drag*" for this quantity.

5. Conclusion

In the foregoing analysis of the external drag of a body which may have an internal duct, terms have been introduced which are generally applicable for both subsonic and supersonic speeds; the terms are defined precisely in the Appendix.

It is realised by the Panel that alternative systems could be devised which would lead to drag components different from those discussed in this Report. It is felt though that the methods of analysis presented here are similar, in the main, to those commonly used in aerodynamics. Some of the drag components are also in common use and where possible the Panel has used the accepted names for these items; in a few cases where a widely used term may be ambiguous (*e.g.* induced drag), alternative names have been suggested.

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APPENDIX

DEFINITIONS OF CERTAIN TERMS USED IN THE DESCRIPTION AND ANALYSIS OF DRAG

In using these definitions, reference should be made to the discussion in the appropriate part of the Report

A. Drag Concepts and Associated Terms

1. EXTERNAL FLOW. The flow of fluid which passes around the body.
2. INTERNAL FLOW. The flow of fluid which passes through a duct in the body.
3. EXTERNAL SURFACE. A surface forming a boundary of the external flow.
4. INTERNAL SURFACE. A surface forming a boundary of the internal flow.
5. PRE-ENTRY STREAM TUBE. The stream tube, extending to the body from infinity upstream, that separates the internal flow from the external flow.
6. EQUIVALENT POST-EXIT STREAM TUBE. The stream tube, extending from the body to infinity downstream, that is assumed to separate the internal flow from the external flow in the absence of mixing.
7. TOTAL DRAG. The force corresponding to the rate of decrease of momentum, in a direction parallel to the undisturbed stream, of the external flow around the body, this decrease being calculated between stations at infinite distances upstream and downstream of the body.
8. NORMAL-PRESSURE DRAG (*or* PRESSURE DRAG). Drag arising from the resolved components of the normal pressure on the boundary under consideration (*see* page 797).
9. TRAILING-VORTEX DRAG (*or* VORTEX DRAG). Drag associated with the trailing vortices. The product of the trailing-vortex drag of a body and its velocity is equal to the work done per unit time in extending the trailing

vortices, and is also equal to the rate of production of kinetic energy within the system.

10. WAVE DRAG. Drag associated with the shock waves.
11. BOUNDARY LAYER NORMAL-PRESSURE DRAG (*or* BOUNDARY LAYER PRESSURE DRAG). The difference between the boundary layer drag and the surface-friction drag.
12. SURFACE-FRICTION DRAG (*or* FRICTION DRAG). Drag arising from the resolved components of the tangential stresses on the surface of the body.
13. BOUNDARY LAYER DRAG. Drag associated with losses in total pressure and total temperature in the boundary layers. It is the sum of the boundary layer normal-pressure drag and the surface-friction drag.

B. Terms Useful in Drag Estimation

1. PRE-ENTRY DRAG. The normal-pressure drag on the outside of the pre-entry stream tube.
2. POST-EXIT DRAG. The normal-pressure drag on the outside of the equivalent post-exit stream tube.
3. INTRINSIC NORMAL-PRESSURE DRAG (*or* INTRINSIC PRESSURE DRAG). The drag arising from the components of the normal pressure on the external surfaces of a ducted body.
4. DATUM INTAKE FLOW. The intake flow that occurs when the boundary of the pre-entry stream tube is unaffected by the presence of the intake.
5. FULL INTAKE FLOW. The intake flow that occurs when, with a pre-entry compression body in position, the boundary of the pre-entry stream tube is unaffected by the presence of the cowl. If there is no pre-entry compression body then full intake flow is the same as datum intake flow.
6. PRE-ENTRY DRAG AT DATUM FLOW. The pre-entry drag that arises when a side intake is operating at datum flow. This drag is zero for a nose intake.
7. SPILLAGE. The amount by which the intake flow is less than the datum intake flow.
8. BASIC SPILLAGE. The amount by which full intake flow is less than datum intake flow.
9. INCREMENTAL SPILLAGE. The amount by which the intake flow is less than full intake flow.
10. SPILLAGE DRAG. The difference between the drag at a given intake flow and the drag at datum intake flow.
11. BASIC SPILLAGE DRAG. The difference between the drag at full intake flow and the drag at datum intake flow.
12. INCREMENTAL SPILLAGE DRAG. The difference between the drag at a given intake flow and the drag at full intake flow.
13. DATUM LIFT COEFFICIENT. The lift coefficient at which, for given Reynolds and Mach numbers, the external drag coefficient is a minimum.
14. DATUM DRAG. The drag at datum lift coefficient and datum intake flow.
15. DRAG DUE TO INCIDENCE, CAMBER AND TWIST AT DATUM LIFT COEFFICIENT. That part of the drag associated with the incidence and with the distribution of camber and twist at datum lift coefficient.
16. WAVE DRAG DUE TO THICKNESS. The part of the wave drag associated with the thickness distribution.
17. DRAG DUE TO INCIDENCE, CAMBER AND TWIST. That part of the drag associated with the incidence and with the distribution of camber and twist.
18. LIFT-DEPENDENT DRAG. The difference between the drag at a given lift coefficient and the drag at datum lift coefficient.

The Definitions of Terms Relating to Various Flow Regimes of a Gas—Some Proposals

by

C. H. E. WARREN and A. D. YOUNG

1. Introduction

In recent years there has been a rapid expansion of the ranges of speed and altitude that are of practical interest to aircraft and missile designers. In consequence, several new terms have been introduced to describe the new flow régimes that require to be considered and, at the same time the meanings of some of the older terms have undergone a measure of modification. The meanings attached to these terms by different workers have not always been consistent, differences have sometimes arisen from the differences of outlook between theoretical and experimental workers or between those concerned primarily with the motion of a fluid and those concerned primarily with the forces on a body in the fluid. To avoid the confusion that may readily arise if such differences become too well established it was felt desirable at this stage to attempt the formulation of unambiguous definitions of the more important terms in current use.

A source of difficulty in this task that must be noted is the fact that some of the terms have been adopted

for reasons other than their etymological aptness to the flow régime or characteristic considered. For example, "transonic speed" suggests a speed increasing or decreasing through the speed of sound. Yet it has come to denote, among other things, the speed of an aircraft not very different from the speed of sound in the undisturbed air at the altitude of flight. The reason for this will be clear from the discussion that follows. Nevertheless the term "near-sonic" would clearly be more apt than "transonic" in this context. Where, however, a term such as the latter has become widely accepted it was felt that it would be unwise to reject it on etymological grounds, provided that a clear unambiguous meaning could be assigned to it.

The definitions are developed and enlarged upon in Section 2, and the more important are summarised, with related terms for completeness, in the Appendix.

NOTATION

a	speed of sound
l	a typical linear dimension
M	Mach number
K	Knudsen number (λ/l)
R	Reynolds number
λ	mean free path of molecules
ν	kinematic viscosity

2. Discussion

An essential preliminary is to define the *speed of sound* at a point in moving fluid. It is the speed with which small disturbances are propagated in the neighbourhood of the point measured relative to axes moving with the velocity of the fluid there. We then define a *Mach number* in general as the ratio of a speed to a related speed of sound. This general concept makes it easy to adopt subsequent and more specific definitions to either a frame of reference associated with a moving element of fluid, or one associated with the aircraft or model past which the fluid is moving. Definitions of such particular Mach numbers readily follow and these then lead naturally to definitions of *subsonic* and *supersonic* speeds associated with the relevant Mach number being less than or greater than unity, respectively. From this follow the definitions of *subsonic* and *supersonic flows*, which are described as flows for which, in the regions considered, the speed is everywhere subsonic or supersonic respectively.

We come next to *transonic flow* which is defined as a region of flow in which there are conterminous smaller regions of subsonic and supersonic flow, each of significant extent for the problem considered. Across the common boundaries of these sub-regions of flow the flow Mach number passes through the value unity. Such mixed flows present special theoretical and experimental difficulties because of the very different manner in which boundary conditions impress themselves on the flow at subsonic and supersonic speeds, and in particular linearised small perturbation theory loses its validity for such flows. The term *transonic flow* is frequently confined to regions where the flow Mach number is everywhere close to unity, and the so-called transonic flow theory is a non-linear small perturbation theory especially developed for such cases; nevertheless, it was felt that the term need not in general be so restricted.

As already remarked the term *transonic speed* has become so widely accepted to mean an aircraft or stream speed for which the Mach number is close to unity, in the range from about 0·8 to 1·2, that it was clearly desirable to retain this definition. At such speeds the flow past bodies of practical interest is generally transonic in the sense already defined, although this will depend on the body thickness and shape. The thinner or more slender a configuration is, and the smaller is its incidence, the nearer the stream or aircraft Mach number must be to unity for the flow engendered to be transonic.

We consider next the term *hypersonic flow*. When an analysis is made of the flow about a body at Mach numbers large compared with unity it becomes evident that the flow characteristics are such as to merit a special name, and the name hypersonic was introduced. As in the case of transonic flow, linearised small perturbation theory loses its validity for the flow of an inviscid fluid at high Mach numbers unless the body concerned is of extreme slenderness. This is because the disturbances in flow speed then introduced by the body cannot in general be regarded as small compared with the speed of sound, and any valid simplifications of the basic flow equations leave them essentially non-linear. A characteristic feature of hypersonic flow is that the overall inclination of the body nose shock is of the same order of magnitude as the mean body slope, so that the region of flow near the body influenced by it is a relatively narrow one between the shock and body surface. The flow of a perfect fluid is then characterised by the fact that an increase of Mach number of the undisturbed stream is accompanied by little change in the velocity distribution, the accompanying changes are essentially in the temperature distribution. The analysis further demonstrates the importance of the so-called hypersonic similarity parameter, formed by the product of the stream Mach number and a representative body slope measured relative to the undisturbed stream direction. It can be shown that the flows of a perfect fluid about bodies of geometrical similarity at high Mach numbers are similar for the same value of this parameter and the breakdown of linearised small perturbation theory is associated with the value of this parameter being of the order of unity or higher.

When we come to consider a real fluid in hypersonic flow it will be clear that since the region of influence of the body is a narrow one the distinction between boundary layer and external flow becomes increasingly difficult to draw with increase of stream Mach number. Problems of skin friction, heat transfer, and so on, therefore have stimulated the development of hypersonic flow boundary layer theories that attempt to take account of this fact. The picture is made more complex by the fact that at very high Mach numbers the temperature changes at the nose shock may be such as to cause dissociation and ionisation, and these effects may in turn modify the flow and, in particular, the development of the boundary layer.

Bearing in mind these different aspects of flow at high Mach numbers that have at various times been associated with the term "hypersonic," it was felt that the best definition of hypersonic flow would be the simplest and most general. With configurations of practical interest the important characteristics of hypersonic flow are in evidence at Mach numbers of the order of 5 or more. *Hypersonic flow* is therefore here described simply as a region of flow in which such Mach numbers occur.

The definition of hypersonic speed readily follows as that of a stream or aircraft for which the Mach number is of the order of 5 or more.

It will be noted that "supersonic" includes "hypersonic" and overlaps "transonic," but by implication it will usually be used to denote the intermediate régime where these other terms do not apply.

Reference is sometimes made in the literature of flow at high Mach numbers to *Newtonian flow*. This is because at such Mach numbers the flow bears a rough overall resemblance to the flow of a fluid postulated by Newton in which all changes produced by a body occurred at the surface of the body and were essentially changes of momentum necessary to change the flow from its undisturbed stream direction to the local surface direction. Thus the zone of influence of the body was confined to its surface, a state of affairs that can be regarded as occurring in the limit of hypersonic flow of an ideal fluid as the stream Mach number tends to infinity. Likewise some qualitative resemblance can readily be demonstrated between formulae for the aerodynamic characteristics of simple shapes at high Mach numbers based on hypersonic flow theory and the corresponding formulae based on the so-called Newtonian flow theory and, by improvements in the latter, differences between the two sets of formulae can be readily reduced.

We come now to consider *continuum flow* and in contrast *slip flow*. All gases consist of molecules in random motion relative to the ordered mean motion. This random motion is characterised by a length called the *mean free path* which is the average distance traversed by molecules between collisions. If this mean free path, denoted here by λ, is very small compared with a typical linear dimension of the body or its boundary layer, then for most purposes the discrete molecular structure of the gas can be ignored and the gas can be regarded as physically continuous. The gas is then referred to as a *continuum*, and the flow of the gas is a *continuum flow*. The ratio of λ to the typical linear dimension, l, is here referred to as the *Knudsen number* (K). The length l at body Reynolds numbers where one can reasonably refer to a boundary layer (*i.e.* $R > 10^2$) may pertinently be taken to be the boundary layer thickness at some datum point, at lower Reynolds numbers a purely geometric dimension of the body is appropriate. Broadly speaking continuum flow will apply for values of K of the order of 10^{-2} or less. It is an essential characteristic of continuum flow that at a solid surface the adjacent fluid can be regarded as at rest relative to the surface, this characteristic is sometimes referred to as the *condition of no-slip*. Since the vast majority of practical problems concern flows which can be regarded as continuum flows they are not usually referred to as such and, in general, a flow may be taken as a continuum flow unless it is specifically indicated to be otherwise.

Where K is small but not insignificant by comparison with unity (*i.e.* of order 10^{-1}), the discrete molecular structure of the fluid plays an appreciable part in determining the character of the flow, particularly near the boundary where the condition of no-slip no longer applies. Such a flow is therefore referred to as *slip flow*. In cases where K is of the order of unity or larger the characteristics of the flow are dominated by the molecular structure of the fluid and collisions of the molecules with the boundary are more important than collisions between molecules. Such a flow is referred to as *free molecule flow*. It will be clear that K increases with decrease of density.

Figure 1 has been prepared to illustrate in a broad qualitative way the boundaries between these various flow régimes in terms of Reynolds number and Mach number.

We come finally to the various types of wind tunnels that have been developed for producing these régimes of flow for test purposes. Their definitions present no

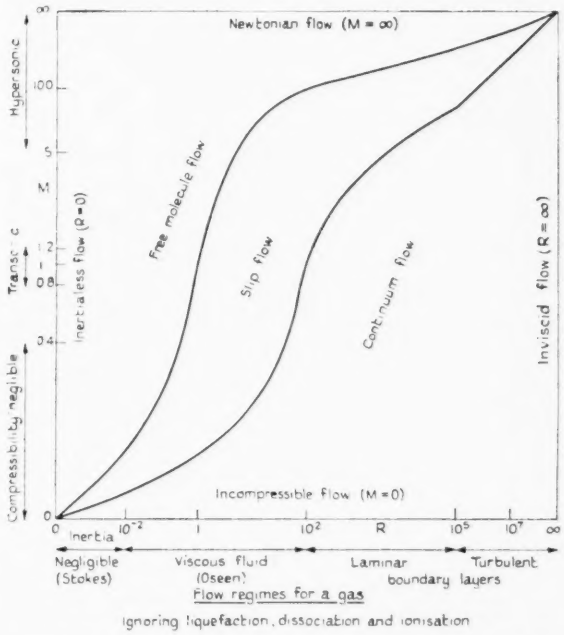

FIGURE 1. The boundaries between continuum flow and slip flow and between slip flow and free molecule flow occur roughly at Knudsen numbers of 0·01 and 1·0 respectively. For Reynolds numbers less than 100 it is pertinent to base the Knudsen number, K, on the typical length, l, but when boundary layers exist it is more relevant to base it on the boundary layer thickness, δ_L (if laminar) or δ_T (if turbulent).

Assuming that $\nu = \lambda a$, where λ is the mean free path, $\delta_L/l = 10/R^{\frac{1}{2}}$ for laminar boundary layers, $\delta_T/l = 1/10^{\frac{1}{2}}R^{1/5}$ for turbulent boundary layers, then the boundaries are given by $M/R = K_1$ for $0 < R < 10^2$; $M/R^{\frac{1}{2}} = 10K\delta_L$ for $10^2 < R < 10^5$; $M/R^{4/5} = K\delta_T/10^{\frac{1}{2}}$ for $10^5 < R < \infty$.

difficulty once the régimes themselves have been defined. It is a matter of some practical interest to note, however, that at the high working section Mach numbers appropriate to a hypersonic wind tunnel the ambient temperature is considerably below the stagnation temperature, so much so that if air is used as the working fluid it is liable to liquefy unless it is preheated. This necessity for preheating when air is used is sometimes regarded as an essential characteristic distinguishing supersonic from hypersonic wind tunnels. Another point of practical interest concerns the tunnel designed for investigating slip flow or free molecule flow. Here the stagnation densities and pressures are generally required to be so low that the latter are most conveniently quoted in microns of mercury or millionths of an atmosphere.

APPENDIX

SUMMARY OF PROPOSED DEFINITIONS

SPEED OF SOUND. The speed with which small disturbances are propagated in the neighbourhood of a point measured relative to axes moving with the velocity of the fluid at that point.

MACH NUMBER. The ratio of a speed to a related speed of sound.

FLOW MACH NUMBER. The ratio of the speed of an element of fluid relative to a solid boundary (*e.g.* aircraft or wind tunnel) to the local speed of sound.

STREAM MACH NUMBER. The flow Mach number at points where the flow can be regarded as uniform.

AIRCRAFT *or* FLIGHT MACH NUMBER. The ratio of the speed of an aircraft relative to the undisturbed air to the speed of sound in the undisturbed air at the altitude of flight. (This is the same as the stream Mach number of the undisturbed air relative to axes fixed in the aircraft.)

SUBSONIC SPEED. A flow, stream, or aircraft speed for which the flow, stream, or aircraft Mach number is less than unity.

SUPERSONIC SPEED. A flow, stream, or aircraft speed for which the flow, stream, or aircraft Mach number is greater than unity.

SUBSONIC FLOW. A flow in which, in the region considered, the speed is everywhere subsonic.

SUPERSONIC FLOW. A flow in which, in the region considered, the speed is everywhere supersonic.

TRANSONIC FLOW. A region of flow in which both subsonic and supersonic speeds occur, so that fluid particles are accelerated or decelerated through the local speed of sound across the common boundaries of the sub-regions of subsonic and supersonic flow. (The term is frequently confined to regions where the flow Mach number is everywhere close to unity.)

TRANSONIC SPEED. A stream or aircraft speed for which the stream or aircraft Mach number is near unity, usually between 0·8 and 1·2. (At such speeds the flow near the aircraft or model concerned is generally transonic.)

HYPERSONIC FLOW. A flow in which, in the region considered, Mach numbers greater than about 5 occur.

HYPERSONIC SPEED. A stream or aircraft speed for which the stream or aircraft Mach number is greater than about 5.

CONTINUUM FLOW. Flow of a fluid under conditions for which the density is sufficiently high that the molecular structure of the fluid can be ignored and the fluid can be considered as physically continuous. These conditions imply that the ratio of the mean free path of the molecules to a typical linear dimension of the body or its boundary layer (the so-called Knudsen number) is very small, and fluid adjacent to a solid surface can be taken as at rest relative to the surface.

SLIP FLOW. Flow where the mean free path of the molecules is a significant fraction of a typical linear dimension of the body, and fluid adjacent to a solid surface is not necessarily at rest relative to the surface.

FREE MOLECULE FLOW. Flow where the mean free path of the molecules is comparable with, or larger than, a typical linear dimension of the body.

SUBSONIC WIND TUNNEL. A wind tunnel capable of running only at subsonic speeds.

SUPERSONIC WIND TUNNEL. A wind tunnel capable of running at supersonic speeds.

TRANSONIC WIND TUNNEL. A wind tunnel capable of running at transonic speeds.

HYPERSONIC WIND TUNNEL. A wind tunnel capable of running at hypersonic speeds. When air is the medium preheating is usually required to avoid liquefaction in the working section.

LOW DENSITY WIND TUNNEL. A wind tunnel capable of producing slip flow or free molecule flow, characterised by a low stagnation density and stagnation pressure, the latter being of the order of one millionth of an atmosphere.

Radio-Astronomy and Navigation

by

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An outline of the history and present state of knowledge of Radio Astronomy is given, together with a more detailed treatment of the stronger localised radio sources. This is followed by a general account of the ways in which these radio sources may be used, and are being used, as navigational aids. Successful experiments made at Dunmow with 8·6 mm. solar radiation are described. Every effort has been made to ensure that, in this rapidly-advancing field, the information given is as up-to-date as possible. Nearly 300 references to the literature are included.

Introduction

The difficulties of determining latitude and longitude under adverse weather conditions, when neither the Sun nor stars can be sighted, are well-known, and the advantages of a non-visual system of position finding which could operate through clouds or fog are too obvious to require emphasis.

A Radio Sextant, which detects and locks-on to 8 mm. radiation from the Sun, has already been made and tested in America with reputedly excellent results. An analysis of both the theoretical and the practical design factors is given in the present paper, together with the results of successful experiments made in Great Britain.

It is not always possible, however, to make observations in the daytime: to consider a rather extreme case, a submarine in wartime must often rely solely upon stellar sightings made under the cover of darkness, and if several overcast nights are encountered in succession its position may become dangerously uncertain. Again, in some latitudes the Sun remains below the horizon for weeks at a time, and it is therefore not observable on any wavelength. These considerations make it clear that the value of a non-visual position-finding system would be greatly enhanced if it could operate upon other celestial bodies in place of, or in addition to, the Sun.

Here again, the Americans have succeeded in measuring the radiation from the Moon, and although a Lunar Radio Sextant has not yet been made the manufacturers of the Solar Radio Sextant claim that their Lunar model is in an advance stage of development. It is therefore worthwhile to review the present state of knowledge of the power and spectra of all known extra-terrestrial radio sources, with a view to considering how best they may be exploited as navigational aids. For convenience of presentation, this paper arranges the sources under four main headings:—

(1) Galactic Sources:
Examples: The Crab Nebula in Taurus, and the Nebulosities in Cassiopeia.

(2) Extragalactic Sources:
Examples: The Great Nebula in Andromeda, and the colliding galaxies in Cygnus.

(3) The Sun:
(*a*) Thermal radiation from the "quiet" Sun, obeying the Planck Law.
(*b*) Abnormal radiation from Sun-spots and solar flares.

(4) Radiation from the Moon and Planets:
(*a*) Thermal radiation from the Moon.
(*b*) Unexplained signals from Jupiter and Venus.

The popular appelation, "Radio Stars," is a misnomer. The Sun is the only star that is known to emit radio waves. The other localised sources of radio emission which have so far been discovered, and which now number over two thousand, are all much larger objects: they vary from the remnants of supernovae, a few light years in diameter, to entire galaxies with diameters of tens of kiloparsecs*. By comparison with these other sources, the Sun is a very feeble radio emitter, but its relative nearness compensates for its lack of intrinsic radio brightness. The radiation intensity at the Earth's surface is measured in Flux Units; one unit equals 10^{-22} watts per square metre per cycle per second, at some specified wavelength or frequency. The flux due to the "quiet" Sun is about 1·9 units on a wavelength of three metres while at the same wavelength the source known as Cassiopeia A gives 1·7 units. This is the most intense source known (ignoring the planet Jupiter, which emits irregular bursts of more than fifty units), and its distance from the Earth is about six hundred million times that of the Sun. The second most intense radio source is that known as Cygnus A; the flux density at three metres wavelength from this source is 1·2 units. Cygnus A, however, is about four hundred million light years away, or about twenty billion times as far as the Sun.

These figures are far too vast for the imagination to grasp, but it is necessary to make an effort in this direction if the full significance of extra-terrestrial radio energy is to be understood and its possibilities exploited.

Sources such as Cygnus A, which has been identified as two galaxies in collision, must grow slowly in intensity over thousands or even millions of years, but other, nearer, sources may literally flare up overnight. As will

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*One kiloparsec is approximately equal to 3,264 light years.

Yerkes Observatory Photograph

FIGURE 1. THE GREAT NEBULA IN ANDROMEDA.

How our own Milky Way Galaxy would appear if viewed from a distance of 440 kiloparsecs (1,436,000 light years). The Great Andromeda Nebula (M.31) is the nearest spiral galaxy to our own, and is very similar in structure. Two other nebulae appear in the photograph, NGC 205 (the larger) and M.32 (the smaller); they are at approximately the same distance as the Great Nebula.

be explained later, there is good reason to believe that in the years 369, 1054, 1572 and 1604, and for some time after each of these dates, the flux intensity at the Earth's surface, due to the supernovae which marked those years, was much greater than anything existing at the present day. Supernovae are due to explosions of unimaginable violence; at their peak, the radiation output is equal to that of an entire galaxy. Statistically, the occurrence of supernovae is only one per galaxy per 360 years, but statistics are notoriously misleading, and a new supernova may appear in our own galaxy at any time. The possibly startling effects of a new supernova upon present day communications systems are discussed in Appendix II.

The strength of the radio sources is not the only consideration, the spectral distribution of the radiant energy being equally important. In assessing the most suitable wavelengths for use with a radio sextant, or other navigational device, it is necessary to give attention to six principal factors:—

(*i*) The variation with wavelength of the power radiated. This will follow Planck's Law in many cases, but in others the radiation may be in the form of "white noise" or, it may have a unique spectrum.

(*ii*) The variation with wavelength of the attenuation due to the Earth's atmosphere or ionosphere.

(*iii*) The liability of the radiation to fluctuations in strength, due either to irregularities of emission, or to variable attenuation.

(*iv*) The variation with wavelength of the power of unwanted signals; these include the noise of the receiver itself, and radiation from sources whose angular separation from the wanted source is small compared to the beamwidth of the receiving antenna.

(*v*) Any peculiarities of polarisation which may help to distinguish the wanted signal from the unwanted background.

(*vi*) The discrimination (or reciprocal beamwidth) attainable at a particular wavelength for an aerial of finite (and probably small) size.

If the maximum practicable aerial size is considered to be a paraboloid of three or four ft. aperture, which is probably true for marine applications, then for a beamwidth not to exceed one degree, the maximum usable wavelength can be shown to be a little less than one centimetre. The atmospheric attenuation sets a lower limit at a wavelength of about one millimetre, for marine purposes, since the radiation must penetrate the entire depth of the atmosphere and these short wavelengths are very strongly absorbed.

The application of "Radio Stars" to aerial navigation must also be considered, but here the value is less certain. In the first place, even a three-foot aerial dish is a difficult object to site on any but the largest aircraft, especially as most machines are already equipped with a multiplicity of electronic devices and their associated antennae. In the second place, it is generally possible for modern aircraft to fly above the weather so that ordinary visual sightings can be made on Sun, Moon or stars. However, above about 30,000 ft. the atmospheric attenuation is very small, and the use of wavelengths of a millimetre or less, with correspondingly smaller aerials, becomes quite practicable. As will be described later, the Americans have also developed an equipment of this kind, which is at present under test with the U.S.A.F.

There is another field of application for extra-terrestrial radio waves, and that is in connection with the guidance of missiles with very long ranges and high trajectories. The Intermediate Range Ballistic Missiles (I.R.B.M.s) and Intercontinental Ballistic Missiles (I.C.B.M.s) cost tens of thousands of pounds each, and it is imperative that each one flies true to its target, yet some of them reach "all-burnt" at such great heights that ordinary command-links are ineffective. Launching guidance is usually in the form of an inertial guidance system, and terminal guidance is in the form of a homing device such as an infra-red homing system: it is the mid-course guidance that calls for some form of celestial reference. The Americans already have photo-electric stellar guidance systems, and these, together

with the possibility of radio-stellar guidance, are discussed later.

Another market for the manufacture of Solar and/or Lunar Sextants is in connection with the trials of Rocket Test Vehicles. It has been proposed that testing grounds should be equipped with such devices, since the data obtainable from their tracking servos could be used to guide test vehicles on any desired course relative to the Sun or Moon. The present alternative is to use a computer which calculates the necessary co-ordinates from a knowledge of latitude and time.

Outline History of Radio Astronomy

The original discovery that radio waves could be detected from extra-terrestrial sources was made twenty-six years ago, in 1932, by K. G. Jansky, a young radio engineer in the employment of the Bell Telephone laboratories. Jansky, using a hundred-foot long steerable array, was engaged in an investigation of static interference when he discovered a faint but undeniable source of radio noise which could not be attributed to other electrical apparatus or to atmospheric electricity. It took more than a year of continuous, patient observation before he was satisfied that the source was not of this Earth at all, that it exhibited the same apparent movement as the stars, and lay in the direction of the constellation Sagittarius.

The discovery was a nine-days' wonder for the American press, but passed almost unnoticed by the scientific world. It was not until 1938 that a deliberate attempt was made to study cosmic radio noise with specially designed apparatus, and even then it was an amateur who undertook the investigation. G. Reber, using a home-assembled reflector of 31 ft. diameter, and a wavelength of two metres, not only located further radio sources in the directions of Aquila, Cassiopeia, and Canis Major, but he also found that the radio waves did not come from the visible stars: some of the most powerful signals came from apparently starless regions.

Official interest in cosmic radio noise did not begin until 1944, when attempts to locate V.2 rockets by long-range radar were defeated by interference due to galactic sources; yet by the time the war ended radio astronomy was coming into its own, and since then the governments of countries all over the world have been allocating increasingly large sums to assist research in this field, the importance of which it is still difficult to estimate.

The pioneer work of Jansky and Reber showed that the distribution of radio noise over the sky closely follows what is known of the shape of the Galaxy. About 90 per cent of the Galaxy is obscured from telescopic view by the great inter-stellar dust-clouds, but since these clouds are far more transparent to radio waves than to visible light, the new science of Radio Astronomy is building up a truer and more detailed picture. The information provided by radio telescopes is of two kinds; firstly they give the direction, and in some cases the position in space, from which the radiation is coming, and secondly they enable us to infer, from the strength of the signal at various wavelengths, a great deal about the conditions which produce the radiation.

Since radio telescopes cannot be constructed with an aperture-to-wavelength ratio which approaches even remotely that of a conventional telescope using visible light, their discrimination is poor, being usually of the order of several degrees. To attain the aperture-to-wavelength ratio of a twenty-four-inch reflecting telescope receiving yellow light, it would be necessary, for receiving radio waves of one cm. wavelength, to construct a radio telescope with a diameter of ten miles. It is possible to obtain more accurate angular data by interference methods, and, by recording the signals received from a number of small radio telescopes separated from each other by accurately known distances, it has been found possible to determine the position of some of the stronger point-sources to a fraction of one degree. Such an instrument, however, is very inconvenient when it is required to make observations on various different wavelengths, and the need for telescopes of really large aperture was realised as soon as Reber published his early work.

For a long time the further development of radio-astronomy was delayed by the lack of sufficient financial backing, but by 1950 a large transit telescope of 218 ft. aperture was operating at Jodrell Bank, and numerous others were under construction in various parts of the world. The Jodrell Bank Experimental Station has now completed a 250 ft. diameter steerable telescope which has a beamwidth between half-power points of less than one degree at a wavelength of one metre. It is an enormous instrument, with a weight of some 2,000 tons, supported on foundations which incorporate about 10,000 tons of reinforced concrete, yet the angular resolution at even so short a wavelength as one cm. is less than 1/20th of that given by a three-inch optical telescope.

It is clear that, despite the great advances made in the past few years, radio-astronomical techniques have still a long way to go, and it is appropriate at this point to recall that although Galileo is credited with having invented the telescope in 1609 (actually, Hans Lippersheim completed a refracting telescope for the Dutch Government the preceding year), the 200-inch Hale Telescope was not dedicated until 340 years later—in 1948. It is impossible to guess what developments may take place in radio-astronomy in the next 340 years, but they will certainly be striking, and may be of far-reaching importance.

Some idea of the present state of world interest in radio-astronomy may be gained from Table I which lists steerable radio telescopes in operation or under construction.

The Nature of Galactic Radio Sources

For a radio source to be recognised as being probably a galactic object it must satisfy certain criteria, such as appreciable angular extent and intensity. It is generally accepted that some twenty of the known radio sources (numbering nearly 3,000 in all) are actually located in the local Galaxy, and of these,

TABLE I

LARGE STEERABLE RADIO TELESCOPES

Site	*Reflector diam. (ft.)*	*Remarks*
Australia		
Radio Physics Laboratory	210-260	Projected
Radio Physics Laboratory	23-40	Several in operation
France		
Various	23-40	In operation
Germany		
Stockert Radio Observatory	82	Azimuth mounting Completed
Netherlands		
Kootwijk Radio Observatory	82	Azimuth mounting Completed
Kootwijk Radio Observatory	26	Two in operation
United Kingdom		
University of Manchester	246	Reflector swivelling in azimuth
Jodrell Bank	20-35	Several in operation
Various	26	Several in operation
United States of America		
Bureau of Standards	26	In operation
Carnegie Institution	26	In operation
California Institute of Technology	100	Two installations scheduled for 1957
California Institute of Technology	33	In operation
Cornell University	26	In operation
Harvard University	65	Parallactic mounting; completed April 1956
Harvard University	26	In operation
Naval Research Laboratory	52	Azimuth mounting; In operation

(After BRANDT, L. *Interavia*, 1956, No. 11, with alterations.)

eight have been identified with visible galactic objects. These eight sources will be discussed in some detail. Surveys at 21 cm. wavelength have revealed a number of other localised sources, which are associated with known concentrations of inter-stellar hydrogen: these sources are extremely weak emitters, and will not be considered further here.

TAURUS A

"In the first year of the period Chih-ho, the fifth moon, the day chi-ch'ou*, a guest star appeared several inches southeast of Tien-Kuan†. After more than a year it gradually became invisible." This extract is from the "History of the Sung Dynasty." In another Chinese manuscript of the same period this observant astronomer (there is no European record of the occurrence) wrote that "the guest star was as visible by day as Venus; pointed rays shot out of it in all directions, and its colour was reddish-white." From what is now known to be the distance (about 4,000 light years), and the statement of the Chinese astronomer that at its maximum brightness the new star was as bright as Venus, it may be calculated that at the time of the explosion the actual brightness was more than 100,000,000 times that of our Sun.

Bolton, Stanley and Slee[25] first suggested that one of the intense radio sources (OSN2A, or Taurus A) might be associated with the Crab Nebula, and subsequent accurate measurements of the position of the source and its angular dimensions established beyond doubt that this is the case. The Crab Nebula is the expanding gaseous shell of the "guest-star" of 1054 A.D., and is a somewhat shapeless nebulosity with numerous tentacle-like filaments reaching millions of kilometres out into space.

The present diameter of the nebula is about six light years, and it is still expanding at a rate of about 1,100 kilometres per second. At the centre of the nebula two small stars are visible, one of which is thought to be the remnant of the original Star, and has been estimated to be still some 30,000 times brighter than our Sun. Minkowski has calculated that the surface temperature of this remnant is about 500,000°K, and that its radius is only about 1/50th that of our Sun. The temperature of the gaseous shell has been calculated to be 50,000°K, which is far too low to produce the observed intensity of 0·16 flux units (at 100 Mc./sec.) by thermal processes. Taurus A is the third most intense radio source in the sky.

In 1954, the Soviet astronomer V. A. Dombrovsky[58] established that the light from the Crab Nebula is polarised; later T. Walraven of the Netherlands showed that the polarisation varies greatly in different regions. Shklovskii, in 1953, and subsequently Dort and Walraven, developed theories to explain both the polarisation of the light and the unexpectedly high radio intensity, as a synchrotron mechanism resulting from the movement of very high energy electrons in a weak magnetic field. It now seems highly probable that the Crab Nebula and other supernovae remnants are not only powerful radio emitters, but are responsible also for an appreciable fraction of cosmic rays.

CASSIOPEIA A

This is the most intense celestial radio source known. Its angular extent is about four minutes of arc, and the emission intensity at 100 Mc./sec. is 1·7 flux units. Known also as 23NSA, this source was the first to be discovered in the northern hemisphere (Ryle and Smith[213]), but it was not until three years later that Baade and Minkowski, searching with the 200 in. telescope, located the visible counterpart. They found an unknown type of extended gaseous nebulosity, very faint, with great wisps and filaments of turbulent matter in violent motion at thousands of kilometres per second.

There is no satisfactory explanation of the mechanisms by which this source generates radio waves, although some kind of synchrotron process has been postulated. The nature of the object itself has also been a subject for great dispute, but it is now generally believed to be the remains of the 369 A.D. Supernova. The estimated distance is in some doubt, as two different results can be obtained according to the technique

*The 4th July, 1054 A.D.

†The star Zeta Tauri.

employed. The most probable value is something over 9,000 light years.

CASSIOPEIA B AND OPHIUCHUS

Since the star of 1054 A.D. there are only two other well-attested cases of supernovae in the local Galaxy. One of these was observed by the famous Danish astronomer Tycho Brahe in 1572, and the other by his distinguished pupil Johann Kepler in 1604.

The identification of a radio source with Tycho Brahe's Star, the 1572 Supernova, was made by Hanbury Brown and Hazard in 1952. The intensity of this source, Cassiopeia B, at 100 Mc./sec. is 0·017 flux units.

The radio source in Ophiuchus was identified with Kepler's Star, the Supernova of 1604, by the Cambridge Group in 1955. The emission intensity of this source is 0·02 flux units at 100 Mc./sec.

So far, no visible traces of Tycho Brahe's Star have been found, but the remnants of Kepler's Supernova have been clearly photographed, and appear as a fan-shaped nebulosity.

CYGNUS X, AURIGA, PUPPIS A AND GEMINI

At present there are only four other agreed identifications of radio sources with galactic objects; these are the Cygnus Loop Nebula, and the nebulosities in Auriga, Gemini and Puppis. All four are extended gaseous nebulosities of low photographic brightness and filamentary structure.

The Loop Nebula in Cygnus, identified with the radio source Cygnus X, shows shreds of luminous cloud forming a roughly circular pattern of broken arcs. It has been suggested by Oort[179] that such a pattern might well indicate that the nebula is the disrupting shell of a 100,000 year old supernova. The emission intensity of this radio source is 0·07 flux units at 100 Mc./sec.

The filaments of Auriga, Gemini and Puppis show turbulent motion like that exhibited by Cassiopeia A, but the turbulent velocities are less violent, being of the order of a few hundred kilometres per second, and the radio emission is correspondingly weaker.

The Auriga source has an intensity of 0·008 flux units at 100 Mc./sec., while at the same frequency the source Puppis A has an intensity of 0·1 flux units.

The Gemini source, 06N2A, has been identified with the galactic nebulosity IC443[16]. A photograph of this object, taken with the 48 in. Schmidt camera at Palomar, shows that the nebula is roughly circular in shape and about 48 minutes of arc in diameter. The optically bright regions show a filamentry structure. Shklovskii[232] has suggested that the spatial—and frequency—distribution of the radio emission is such as might be expected were the nebula an expanding shell of gas—perhaps a nova or supernova remnant. The intensity of the radio emission at 81·5 Mc./sec. is about 0·06 flux units.

THE FREQUENCY SPECTRUM OF GALACTIC NOISE

Very little reliable information is as yet available either as to the spectrum of galactic background radiation or of the point-sources. Measurements of the frequency spectrum are difficult because the flux intensity is extremely feeble at the shorter wavelengths. The first measurements were made in 1946 by Moxon on wavelengths from 1·5 to 7·5 metres; he concluded that the intensity of noise in the galactic plane varied as $\lambda^{0.8}$, and as $\lambda^{0.1}$ away from the galactic plane. In 1948 Herbstreit and Johler gave a figure of $\lambda^{2.41}$ without differentiating between the noise from different parts of the galaxy. More recent results by the Australian workers and by Hanbury Brown at Jodrell Bank suggest that it is reasonable to conclude that the intensity of the noise from the direction of the galactic plane varies as $\lambda^{0.7}$.

Measurements of the noise distribution from some of the more intense point sources have been made by Bolton and Slee over the frequency range 40 to 160 Mc./sec. For the sources in Cygnus and in Centaurus they find that the intensity varies as $\lambda^{1.0}$.

GALACTIC RADIO NOISE SOURCES—SUMMARY

The present knowledge of radio sources which have been identified with visible objects in the local Galaxy permits of only one general conclusion: the sources represent a type of photographically visible object which, until a few years ago was unknown and which must still be regarded as of rare occurrence. The principal characteristic of this class of object is an appreciable extension of diffuse gas of very low luminosity. It is still uncertain whether the objects are of variable origin or whether they all represent different forms of supernova remnant, but the latter view is gaining increasing support.

The Nature of Extragalactic Radio Sources

Apart from the galactic concentration of a very small number of localised radio sources described in the preceding section, the thousands of known "radio stars" are distributed isotropically and are believed to be extragalactic. Only a small number have been identified with visible or photographic objects, and the nature of the remainder is unknown, although it has been suggested that many of them may be colliding galaxies at vast distances, beyond the reach of our largest optical telescopes.

The identified extragalactic radio sources fall into two main categories:

(*i*) Normal Extragalactic Nebulae, a number of which have been shown to generate a total radio flux comparable in magnitude with that from our own Galaxy.

(*ii*) Colliding Galaxies, which may have a luminosity more than 10^5 times that of our own Galaxy. It is not known how the radio emission varies with the type of galaxy or their relative velocity, but since the probability of collision varies as the square of the nebular density, the spatial density of the radio sources may be expected to be markedly greater in the large Supergalactic Clusters. The small amount of available evidence supports this theory.

Since the most powerful of the extragalactic sources is one belonging to the second category, those radio

sources known to be associated with abnormal extragalactic objects will be dealt with first, and those normal extragalactic nebulae which are strong radio emitters will be dealt with separately. The unidentified sources will be dealt with in a third sub-section.

1. THE CYGNUS A, AND OTHER ABNORMAL EXTRAGALACTIC OBJECTS

Cygnus A is the second most powerful radio source in the sky, the intensity at 100 Mc./sec. being 1·2 flux units. This is one of the most remarkable facts in the whole science of radio astronomy, since the distance of the source is known to be some 400,000,000 light years from which it is easy to calculate that the total radio power emanating from this source is of the order of 10^{30} megawatts. The first observation of a radio source in the direction of Cygnus was recorded by Reber[208], but his equipment did not permit of accurate determination of the position. Accurate location was not achieved until 1951, when the Cambridge Group obtained very precise measurements with their twin-aerial interferometer. Using the Cambridge data, Baade and Minkowsky[14] were able to search for a visible counterpart to the radio source, with the 200 in. Palomar telescope. Eventually, they succeeded in obtaining a photograph of a very remarkable object—two spiral galaxies in collision. The collision velocity of the galaxies is estimated at about 40,000 kilometres per second, and the diameter of the region of collision is about 30,000 light years.

Perseus. The Cygnus A radio source is the first to have been identified as galaxies in collision, but now several other sources are believed to be of a similar nature. The Perseus Supergalaxy is a cluster of some 500 nebulae at a distance of 20 megaparsecs (65,000,000 light years). The Cambridge Group has identified the Perseus radio source with the object N.G.C. 1275, two of the Perseus galaxies in collision. This source has an intensity of 0·014 flux units at a frequency of 100 Mc./sec.

Hydra. This source has an intensity at 100 Mc./sec. of 0·026 flux units. It has been identified by Baade and Minkowski with an object believed to be two galaxies in collision.

Centaurus A. (N.G.C. 5128). In the direction of the constellation Centaurus is to be seen one of the richest and most distinct of the Supergalaxies, comprising some 300 separate galaxies, at a distance of 50 megaparsecs (163,000,000 light years). On photographic plates the visible counterpart of the radio source Centaurus A appears as a bright circular nebulosity with a dark band across it: it is believed to be a collision between two of the Centaurus galaxies. The intensity of this source is 0·17 flux units at 100 Mc./sec. Mills (1953) has shown that Centaurus A displays two subsystems of radio emission, one associated with the band of dust crossing the nucleus and the other forming an immense corona which surrounds the whole system.

Virgo A. The Virgo cluster of galaxies incorporates some 2,500 nebulae at a mean distance of 4·1 megaparsecs (13,400,000 light years), and is one of the most conspicuous of the Supergalaxies. The object which has been identified with the Virgo A radio source is a globular nebula, the main body of which photographs red. Extending out from the reddish nucleus is a peculiar jet, a blue-white streak of intensely luminous gaseous material nearly 2,000 light years in length and about 200 light years in diameter. The intensity of the radio emission at 100 Mc./sec. is 0·11 flux units.

The ratio of radio to optical emission of the Abnormal Extragalactic Objects is of the order of 10^{-3} (reaching unity in the case of Cygnus A), and the mechanism by which such high intensities of radio emission are generated is a problem which is still far from being solved. In collisions between galaxies, the interstellar distances are so great that individual stellar collisions will be extremely rare, but an appreciable part of the galactic masses will be composed of inter-stellar dust and gases which will collide at immense velocities, probably reaching thousands of kilometres per second, and in this immense exchange of energies the clue to the generation of the radio emission may well be found.

2. ANDROMEDA A, AND OTHER NORMAL EXTRAGALACTIC NEBULAE

Andromeda A. The great nebula in Andromeda appears to the naked eye as a faint haze of light against the background of the night sky. It must therefore count among the earliest known celestial objects, but it was only in 1924 that Hubble, using the 100 in. Mount Wilson telescope identified the object as a separate island universe at an immense distance, thus changing our whole conception of Cosmology.

Actually, the nebula M.31 (or N.G.C. 224) is the nearest of the spiral galaxies, and it is now known that it closely resembles our own Milky Way Galaxy in structure. As seen through the largest telescopes it is an oval form, with a clearly defined spiral structure, tilted at an angle to us. It is estimated to lie at a distance of 440 kiloparsecs (1,436,000 light years) and to have a diameter of approximately 50,000 light years. It is believed to be approaching our own Galaxy at a velocity of about 300 kilometres per second.

The nucleus is relatively small and dense, a flattened mass which has been described as resembling a heap of pepper. The individual " pepper grains " are stars, billions of them, the most conspicuous of these central stars being red giants with a luminous intensity 200 times that of our own Sun. Chains of blue " super-giants " extend out from the nucleus, each one hundreds of times brighter than the red giants; in fact these blue " super-giants " are the brightest stars known. Baade (1946) has shown that most of the inter-stellar matter is concentrated in the spiral arms, each chain of blue super-giant stars illuminating in profile a dark mass of dust and gas. The regions between the spiral arms of the galaxy are practically empty, and Baade has suggested that the existence of spiral arms may actually depend upon the presence of great masses of inter-stellar material, so that dust-free galaxies could not possess a spiral structure. Such dust-free galaxies are well known in the large clusters of galaxies and Spitzer has suggested that galactic collisions are frequent in

such clusters, the galaxies sweeping each other free of inter-stellar debris.

Radio emission from M.31 was first detected by Hanbury Brown and Hazard[89] at Jodrell Bank. They showed that the integrated emission from the Andromeda nebula is about three times the integrated emission from our own Galaxy. By radio light, Andromeda is much larger than the visible object, and of a different shape. Baldwin (1954) has shown that there are sources of radio energy extending to very great distances normal to the spiral plane. As a crude model, he has suggested that the observations can be explained by a distribution of sources following the stellar distribution in the spiral plane of the galaxy, which contributes one third of the total intensity, together with a distribution of sources having spherical intensity and extending to radial distances greater than 10 kiloparsecs (33,000 light years) which contributes the remaining two thirds of the radio energy. The centre of the sphere is approximately coincident with the centre of the spiral disc. It is considered by the Cambridge Group that the most probable explanation of the radiation from this invisible sphere, is that it is radiation emitted by high-velocity electrons moving in magnetic fields (synchrotron radiation).

The intensity of Andromeda A, at 100 Mc./sec. is 0·02 flux units.

The Magellanic Clouds. These are the nearest of the external galaxies, and the most easily studied. The Larger Cloud contains over 200,000 stars brighter than 0·0 absolute magnitude, and 750 stars brighter than −5·0 absolute magnitude. It also contains far more dust than the Small Cloud, and seems to be in an early stage of evolution from irregular shape to a symmetrical form. Very close inspection shows faint traces of spiral arms. The galaxies are visible to the naked eye and early travellers called them the "White Clouds."

Study of the radio emission of the clouds is difficult because both have a relatively low surface brightness compared with irregular variations in the background radiation. Mills[156] has made a detailed study and gives the following figures:—

L.M.C. emission intensity at 86 Mc./sec. = 0·2 flux units.

S.M.C. emission intensity at 86 Mc./sec. = 0·03 flux units.

Distance of S.M.C. is 47 kiloparsecs = 153,000 light years.

Distance of L.M.C. is 42 kiloparsecs = 137,000 light years.

The Pinwheel Nebula. As its name suggests, this is a spiral nebula with well-opened spiral arms, resembling the familiar firework. It lies in the direction of the Boötes constellation, at a distance of 1,100 kiloparsecs (3,600,000 light years) and has an approximate diameter of 23,500 light years. This galaxy (M. 101, or N.G.C. 5457) has an intensity at 100 Mc./sec. of 0·015 flux units.

N.G.C. 55. There is some difficulty in classifying this galaxy, as it is seen nearly edge-on, but there is fairly strong evidence for classification as a magellanic type ("incipient spiral"). The intensity at 86 Mc./sec. is 0·0002 flux units, which is at the limit of detectability.

N.G.C. 253. This galaxy is a type 5c, that is to say an open spiral, like the Pinwheel Nebula. Its distance is 1,300 kiloparsecs (4,242,000 light years), and its diameter is about 26,000 light years. The intensity of radio emission at 86 Mc./sec. is 0·011 flux units.

The normal Nebulae show a ratio of radio to optical emission of about 10^{-6}. There are still many unsolved problems; the methods by which these galaxies generate radio energy, whether different types of galaxy vary in their emission, and whether such variations are associated with differences in stellar population and the place of the galaxy in the evolutionary sequence.

3. UNIDENTIFIED RADIO STARS

One of the most striking features of all surveys of radio stars which have been made in both the northern and the southern hemisphere, is the failure to associate more than a very small proportion with optically identifiable objects. It now appears, in fact, that the largest class of radio stars consists of objects at such vast distances that even the largest telescopes cannot detect them.

Radio Waves from the Sun

By comparison with the "radio stars," the Sun is an insignificant emitter of radio waves. Table II illustrates this fact by comparing the emission from the Sun with that from the two best-known galactic sources, Cassiopeia A and Taurus A, the distances all being normalised to ten parsecs (32·6 light years).

The visible radiation from the Sun is surprisingly steady, considering all the disturbances that take place in the interior and on the surface of the Sun. The brightness of sunlight varies by only about one per cent year after year, whereas the solar radio emission is a flickering, pulsating radiation. During a single day the radio emission may flare up frequently, the intensity increasing by a factor of from ten to several hundred times. More rarely, it may grow many thousands of times more intense in a few seconds.

The very short-wave radiation from the Sun (measurements made from high altitude rockets have covered the ultraviolet region down to about 1,000 Ångstrom units) is also appreciably variable, being much greater at sunspot maximum than at sunspot minimum. This is shown in various ways such as the increase in the diurnal variation of the components of the earth's magnetic field, which is considerably greater at sunspot maximum than at sunspot minimum, and in the behaviour of the ionosphere through the sunspot cycle. In addition to this type of variation, there is a greatly enhanced emission of short-wave radiation from the

TABLE II

Power of Radio Sources normalised to a distance of ten parsecs, in Flux Units at 100 Mc./sec.

CASSIOPEIA A	$1{\cdot}6 \times 10^{5}$
TAURUS A	$1{\cdot}06 \times 10^{5}$
SUN	$4{\cdot}75 \times 10^{-15}$

Sun during a solar flare, and it can happen that the short-wave radiation from the flare itself may be as great as that from the entire remainder of the Sun's surface.

The Sun is enveloped by tenuous high-temperature gases which constitute the solar atmosphere. The visible disc of the Sun is termed the photosphere and is at an effective temperature of 5785°K. Beyond this, and extending for a radial distance of some 40,000 kilometres, is the chromosphere, which has an apparent temperature (from spectral line broadening) of about 8000°K. Solar prominences are tremendous upsurgings of gas from the chromosphere, which sometimes shoot out to distances of hundreds of thousands of kilometres. Beyond the chromosphere lies the solar corona, extending to some seven million kilometres from the surface of the photosphere. Before the advent of radio astronomy, the temperature of the corona was thought to be no higher than that of the chromosphere, but it is now known to be much higher, of the order of a million degrees Absolute. There is some evidence of local regions of ten million degrees or more and, also, that the temperature decreases with radial distance.

The intensity of the solar radio emission varies very markedly with wavelength. The intensity of one cm. radiation is very steady, whereas at 150 cm. the radiation is subject to violent fluctuations. Between peaks the noise level does not fall to zero, but remains at a basic level (the "quiet sun" radiation) which hardly ever varies at the shortest wavelengths, and at the larger wavelengths is always detectable between peaks. This base level is related to the Sun's thermal energy.

The coronal regions are highly ionised and completely prevent radio waves longer than a critical wavelength from passing through. The point of cut-off is variable, depending upon the number of electrons present in unit volume. Optical measurements can be used to determine the electron density at various heights above the photosphere, and it is thus possible to ascertain where the radio waves of different wavelengths which escape from the Sun must have originated. The longest wavelengths can come only from the outer corona, the shortest from as low as the chromosphere.

At least five components of solar radiation are known: (*a*) quiet thermal noise, (*b*) steady sunspot noise, (*c*) noise storms which are composed of short bursts and possibly a steady component, (*d*) outbursts which are associated with solar flares, and (*e*) isolated unpolarised bursts.

The amount of solar radio noise for various components as a function of wavelength λ and frequency ν is given in Table III. T_a = apparent temperature = black body temperature of the visible solar disc to give the measured amount of radiation.

The mean intensity of the "typical" noise storm would be exceeded on about 10 days per year at sunspot maximum. The mean intensity of all storm noise at sunspot maximum is about one-sixth that of a typical noise storm.

The intensity of the "typical outburst" would be exceeded by about 100 outbursts per year at sunspot maximum. The life of a typical outburst is 10 minutes. The mean flux of outburst radiation for a sunspot maximum year is 1/100 of a typical outburst flux.

The quiet values in the table refer (as far as possible) to zero sunspot activity. The sunspot minimum data are obtained by extrapolating observations made before sunspot minimum.

The corona is believed to be very extensive at long wavelengths and, for example, it is calculated that for a wavelength of 7·9 metres the effective radius is five times the photospheric radius. The study of these extremely tenuous regions has been greatly assisted by observations of the occultation of radio stars by the Sun. Machin and Smith[144] concluded from their observations that the emission from a radio star is affected up to distances of ten photospheric radii.

The solar surface possesses a granular appearance; occasionally granules are seen to separate and to leave a relatively dark area, known as a pore. The union of several pores gives rise to a sunspot. At intervals, sudden blazes of intense light, which may cover an area of more than 10^9 square miles of the solar surface, occur in the vicinity of sunspots; these are termed solar flares. The radiations from a solar flare are summarised below:

The wave radiation reaches Earth after about 8 min. 20 sec., causing the so-called simultaneous effects, in contrast to the delayed effects caused by the much slower-moving particles.

SIMULTANEOUS EFFECTS

The sudden increase in the intensity of ultra-violet radiation causes a greatly increased number of free electrons to be present in the Earth's ionosphere; this in turn causes severe disturbances to the reception of radio signals, sudden enhancement of atmospherics, and a magnetic crotchet.

DELAYED EFFECTS

Particle radiation is of two kinds: one group is identical with primary cosmic rays, which travel at about 40,000 kilometres per second and reach the Earth in less than one hour. The other group takes about 26 hours to reach the terrestrial atmosphere, and is believed to consist of fully ionised hydrogen, *i.e.* of protons and electrons, so that the stream as a whole remains neutral. On entering the atmosphere these

TABLE III
SOLAR RADIO EMISSION (SOLAR NOISE)

λ cm.	ν Mc./sec.	*Quiet T_a in °K*		*Flux Units*				
				Quiet		*Associated with sunspots* (proj. area = 0·005 disc.)	*Typical noise storm*	*Typical outburst*
		Sunspot maximum	*Sunspot minimum*	*Sunspot maximum*	*Sunspot minimum*			
600	50	1,100,000	1,100,000	0·6	0·6	0·0	40	1,200
300	100	1,000,000	900,000	2·1	1·9	0·0	200	800
150	200	900,000	600,000	7·5	5·0	0·5	100	200
60	500	580,000	230,000	30	12	19	5	50
30	1,000	230,000	100,000	48	21	60	0	30
15	2,000	90,000	49,000	75	41	65		20
6	5,000	31,000	24,000	160	124	70		13
3	10,000	17,000	15,000	350	310	70		10
1·5	20,000	10,000	10,000	840	840			
0·6	50,000	6,400	6,400	3400	3400			

particles give rise to two main effects: one is to cause world-wide disturbances of the Earth's magnetic field ("magnetic storms"), the other is to produce brilliant displays of aurorae.

Radio Emission from the Moon and Planets

THE MOON

The Moon is a continuous source of very weak radio signals. There are two components; the first is actually reflected solar energy, just as moonlight is reflected sunlight, and it has the characteristic spectral distribution of radiation from a body at about 6,000 degrees absolute: the second component is due to the Moon's thermal energy, and its spectral distribution agrees with the much lower temperature of the Moon.

Dicke and Beringer (1946) first reported some measurements of the temperature of the nearly full Moon. Later, an extended series of observations was conducted by Piddington and Minnet (1949), which established the variations of temperature with the phases of the Moon. Piddington and Minnet received lunar radiation in a 15 Mc./sec. band centred at 24,000 Mc./sec. (1·25 cm. wavelength), using a 44 in. paraboloid to reflect the energy into a waveguide horn. Accurate alignment of the beam was made by means of a telescope attached to the reflector. The beamwidth between 3 db. points was three-quarters of a degree. A Dicke-type differential receiver was employed, and the output recorded on a recording milliameter. The overall sensitivity was such that radiation equivalent to an aerial temperature change of 1·2 °K., produced an output equal to the receiver noise power.

The most remarkable feature of Piddington and Minnet's results is that the microwave radiation from the Moon is not in phase with the infra-red emission and the reflected light, but lags behind them by about 45 degrees. The thermal radiation in the infra-red is at its maximum at full Moon, but thermal radiation at 1·25 cm. does not reach its maximum until the Moon is in its gibbous phase, 3·7 days after the full Moon.

Sinton (1955)[233] has shown that the thermal radiation from the Moon is 1/60th to 1/20th that of the Sun, at a wavelength of 1·5 mm. His apparatus consisted of a Golay infra-red detector with a quartz window, and a 24 in. searchlight modified to form a reflecting telescope. This technique appears to be capable of considerable improvement, as Sinton has himself suggested, and the apparatus is considerably less expensive than its microwave analogues.

Since the temperature of the lunar surface varies widely, the thermal radiation also shows great variation. The following temperatures are quoted from "Astrophysical Quantities."

Surface temperature, Full Moon, Centre,
120 °C 393 °K
Surface temperature, New Moon, Centre,
– 130 °C 143 °K
Sub-surface temperature, at all times,
– 40 °C 233 °K.

JUPITER—THE GIANT PLANET

The largest of the planets, Jupiter has a diameter 11·2 times that of the Earth (nearly 90,000 miles), and a mass 318 times as great. The gaseous atmospheric envelope is so opaque that even infra-red radiation cannot penetrate, and infra-red photographs have disclosed no sign of a solid surface. Jupiter has an average density of 1·34, which is so low that a major part of the volume must be composed of gaseous material. Wildt has calculated that Jupiter has probably a rocky inner core with a radius of about 22,000 miles, enclosed by a shell of ice about 16,000 miles thick, and then an atmosphere of about 6,000 miles in depth. The mass of the atmosphere, per unit surface area of the planet, is about 7×10^5 what it is on Earth, also the force of gravity is much greater (2·7 Earth g's). The greater part of the atmosphere must therefore be at a pressure of at least 10^6 terrestrial atmospheres. Pressures of this order would compress most substances to great densities, but there are exceptions: hydrogen, helium, methane, ethane and ammonia. Spectroscopic examination shows only methane and ammonia, the former being greatly in excess. Hydrogen and helium cannot be detected by this form of spectroscopic analysis, but are undoubtedly present. The temperature of the outer layers of the atmosphere is about – 140 °C (133 °K).

The discovery that Jupiter emits intense bursts of radio energy was made by Burke and Franklin[38] and immediately other investigators began a search of their past records of cosmic noise, looking for signs of Jovian radiation. Some records taken at 18·3 Mc./sec. in 1950-51 showed series of bursts which had previously been dismissed as terrestrial interference, and a detailed analysis of these records showed that the radiation was definitely from Jupiter.

The Jupiter signals are of a peculiar type, coming in groups of bursts of extremely high intensity, frequently greater than that of any other known discrete source. Many bursts of intensity greater than 50 flux units have been recorded. Bursts have durations of about a minute or less, groups last about an hour. The cause of the radio emission is unknown; lightning discharges have been suggested, but these would require an energy content of about 10^{14} times that of terrestrial lightning in order to account for the extraordinary radio intensity.

The source of the disturbance coincides with a particular spot, subtending an angle of less than one minute of arc, in the Jovian South Temperate Belt. It is not the famous Red Spot.

VENUS

J. D. Kraus, of Ohio State University, detected radio emissions from the planet Venus in May 1956. The announcement of the discovery, and of subsequent detailed observations, was made in July of the same year[127].

Like Jupiter, the visible surface presented by Venus consists only of clouds; the resemblance to Jupiter ends there, except for the matter of radio emission. Venus has a diameter of 12,400 km., or about 0·97 that of the Earth. The mass is 0·815 that of Earth, and the gravity is 0·86 of Earth's gravity. The temperature of the daytime cloud surface is 370°K. The total atmospheric pressure is about 200 mm. of mercury, and it is estimated that about 50 per cent of the atmosphere is carbon dioxide.

The radio emissions are of two different kinds. Class 1 signals appear on the recorder tape as a succession of randomly spaced sharp spikes each representing a burst of one second duration or less. Bursts are observed to pass through peaks spaced about 90 minutes apart, at which times they are most frequent and intense. The peak power flux intensity of the signals has often been recorded at several times the value of the Cygnus A radio-source at the same frequency (26·7 Mc./sec.). A fairly representative value is 8·9 flux units. Kraus has calculated that lightning discharge phenomena on Venus, of the intensity of the terrestrial variety, would have more than enough power to be the cause of the observed emissions.

Class 2 signals are of a more sustained type, lasting for one second or considerably more, and appear to be modulated at audio-frequency. Modulation frequencies in the neighbourhood of 15, 60, 125 and 150 c./sec. have been noted. The emissions are sufficiently like terrestrial radio telegraphy signals to have been mistaken for interference from radio stations. Class 2 signals appear to be strongest when Class 1 signals are also present. Pulses may occur, of about one second duration, at intervals of a few seconds to a minute or more. The bandwidth has been estimated to be at least 2 Mc./sec. The pulses are rarely observed for more than 5 to 10 minutes at a time.

EFFECTS DUE TO INTER-STELLAR HYDROGEN

The effects caused by the vast inter-stellar clouds of hydrogen gas are of particular interest because they represent the only part of radio astronomical studies in which spectral line phenomena are concerned, as distinct from wide-band noise.

In the hydrogen atom there are two possible orientations of the electron spin in the weak magnetic field associated with the nucleus, and the energy difference between these states is such that an electron transition gives rise to emission at a frequency of 1,420·405 Mc./sec. (about 21·1 cm. wavelength). The probability of any arbitrary hydrogen atom spontaneously undergoing such a transition is very low; on the average a hydrogen atom in free space exhibits the transition only about once in 11,000,000 years. Furthermore, the mean density of hydrogen in inter-stellar space is extremely low, of the order of one atom per cm.^{3} (at room temperature and atmospheric pressure, 1 cm.^{3} of hydrogen contains about $2{\cdot}5 \times 10^{19}$ atoms). However, the hydrogen clouds stretch out over enormous regions in the central galactic plane, a pancake-shaped volume 81,500 light years in diameter and about 650 light years thick, and van de Hulst predicted in 1945[252] that the hydrogen radiation should be detectable. An extensive search was undertaken for the 21·1 cm. radiation, and in 1951 it was found, almost simultaneously by workers at Harvard and in Holland and Australia.

The importance of this discovery can scarcely be over-estimated, since it provided a method for investigating the structure of the Galactic System which is far more direct than those previously available: for the first time it became possible to study the clouds of hydrogen gas and, by measurement of the Doppler frequency shift of the 21·1 cm. line, to determine the velocity of the clouds relative to the Earth. Again, because of the dense optical obscuration of the Galactic centre by inter-stellar dust clouds, it is quite impossible to observe this region with conventional telescopes: the information obtainable about the Galactic System by optical means is very vague, the first detailed results came from recent work with radio telescopes. Owing to the small absorption which the dust clouds exert upon 21·1 cm. radiation, it is possible to observe this emission from great distances and an extensive mapping of the intensity and other characteristic properties of the hydrogen radiation over the whole sky has been undertaken by several groups of investigators.

Another valuable application of the discovery of hydrogen radiation is to use absorption techniques for the measurement of the distances of galactic radio sources. It is assumed that the radiation from the source under investigation is continuous and does not show line structure at 21 cm. When the radiation penetrates through hydrogen clouds in the Galaxy there

will be absorption at the line frequency, whereas the emission at neighbouring frequencies will be unaffected. It follows that, provided the spatial distribution of the hydrogen is known, the distance of the source can be computed from the extent of the absorption. The absorption will not necessarily occur at 21 cm., since in general there will be a Doppler shift due to the motion of the hydrogen clouds. The method is only applicable to sources situated within the Galaxy: the only information obtainable about extragalactic sources is a confirmation that they are outside the Galaxy. However it is possible, by measuring the Doppler shift, to ascertain the velocity of recession of extragalactic nebulae, and then to determine their approximate distance from Hubble's relation between distance and velocity of recession.*

Radio Studies of Meteors

The popular name of "shooting stars" well describes the appearance of meteors, which are known to consist of small pieces of stone and iron which approach the Earth from outer space at speeds up to 72 km. per second, and which are burnt-up by friction when they enter the Earth's atmosphere.

Measurements of the geocentric parallax of individual meteors show that they occur at heights of 70 to 130 km., while velocity measurements show that they enter the atmosphere with velocities of from 11 km. per second to 72 km. per second, the average being about 40 km. per second. The majority of meteors are sporadic, *i.e.* they appear to approach the Earth from random directions and with random velocities. The total number entering the atmosphere every 24 hours is about 10^{10}, and the total mass of this daily intake is between 1,000 and 2,000 kgm.

It is now known that all the sporadic meteors are members of the solar system, moving around the Sun in short period orbits. In addition to the sporadic meteors there are occasional meteor showers, which may last from a few hours to several days, and which temporarily increase the rate of incidence of meteors by a large factor. Many of these showers recur regularly on the same dates each year.

The primary problem in meteor astronomy is to find the connection between all these bits of cosmic debris and the solar system: is it part of the primeval matter, or has it all arisen from disintegration of planetary bodies at a later date? In recent years, great advances have been made in the study of meteors by the application of radio echo techniques. By studying the radio echoes scattered from the ionised trails left by these bodies, systematic information has been obtained about the distribution of sporadic meteors and also about meteor showers.

Apart from the purely astronomical problems, the radio echo study of meteors has also given valuable information about the physics of the upper atmosphere, and has led to important practical applications in the Janet Communication System, in which teletype information is beamed towards the ionosphere and is returned to the ground at distances up to 1,000 miles by reflection from meteor trails. Surprising as it may seem, the incidence of meteors is sufficiently high for the Janet System to be able to transmit information at an average of 60 words per minute throughout the 24 hours.

*Hubble found that the speeds at which individual nebulae are receding from us are approximately proportional to their distance. A nebula at 10,000,000 light years has a velocity of about 900 miles a second, and the velocities of other nebulae are, at least approximately, proportional to their distances.

Military and other Applications of Radio Astronomy

RADIO SEXTANTS

The Radio Sextant, operating upon solar radio emission, is already an established fact. Experiments by the Collins Radio Company of Iowa, over the past ten years, have led to the development of a number of prototypes for military use, and further research is being done at the Naval Research Laboratory. Nearly two years ago, the U.S.S. *Curtiss* was equipped with one of the Collins' models, and the equipment is reported to have functioned perfectly even under very bad weather conditions. An improved version has been developed for the Floating Laboratory, U.S.S. *Compass Island*: this advanced design is operated in conjunction with an electronic navigational computer. It is mounted on a gyro-stabilised platform, and is enclosed by a pneumatic radome. Conventional tracking mechanisms, employing a spinning dipole, are used to keep the equipment locked-on to the Sun.

The foregoing models operate on Q-Band, at an approximate wavelength of 8 mm., but the manufacturers are reported to have developed a shorter wavelength version, of smaller physical dimensions, for use on large aircraft; trials are being made by the U.S.A.F.

Collins Radio Company estimate a potential commercial market for the Marine Radio Sextant of more than 15,000, and they state: "Three types of this equipment are possibilities; All-Weather Equipment, with accuracy equal to optical; All-Weather Equipment with precision greater than optical; and Nocturnal Equipment, capable of taking readings on lunar radiation." No details have been released of the proposed Lunar Sextant, but the published work of Edison Petitt[191, 192, 193] of the Mount Wilson Observatory, and of W. M. Sinton[233, 234] of Harvard College Observatory, indicates that 1·5 mm. is a practicable wavelength.

The operation of Radio Sextants is not necessarily confined to solar and lunar radiation; "radio stars" and artificial satellites may both be used as navigational references. With "radio stars" there is the difficulty that the flux intensity at very short wavelengths is exceedingly low (of the order of 10^{-26} watt./m./c./sec.) and the longer wavelength radiations, which are more powerful, would require the use of inconveniently large antennae to give sufficient positional accuracy. There is, however, one ray of hope for the use of millimetric Stellar Radio Sextants; the actual limitation is signal-to-noise ratio, and the application of the newly developed molecular amplifiers (MASERS or parametric amplifiers) which have unprecedentedly low noise

figures and therefore offer great possibilities. Artificial satellites offer much greater possibilities; at heights of a few thousand miles the orbital velocities are low enough for tracking to be quite simple (actually, of course, it is the angular velocity which is the limiting factor), and the weight of a millimetric transmitter powered from solar batteries would be only a fraction of that of the second Russian satellite. It has been suggested for decades that if three or more artificial satellites could be placed in stable orbits, they would provide a celestial reference permitting navigational accuracy of a new order, and present-day achievements with satellites suggest that this may be possible within a few years. There is, however, a serious difficulty in that the rapid precession of the orbits makes the task of computing tables of positions for some years ahead a very complicated one.

As has already been mentioned, a further wide new field of application for Radio Sextants is now opening-up in connection with Rocket Test Vehicle trials.

MISSILE GUIDANCE

The obvious possibilities of applying celestial radio sources to the guidance of missiles are rather more complicated than appears on the surface. It is necessary to appreciate something of the complex new Missile Systems Strategy.

The Intercontinental Ballistic Missile (I.C.B.M.) with a maximum velocity of a Mach number of 15-20 and range of 4,000 to 5,000 miles, is at present invulnerable when in flight, and almost invulnerable when on its launching platform. The proposed use of deep underground—or even of underwater—launching installations would make these sites proof against anything short of a direct hit with a nuclear warhead. At some future date it may prove possible to intercept I.C.B.M.s in flight, but at present the aggressor has a marked advantage over the defence. Plans have been drafted for providing some I.C.B.M.s with anti-anti-missile missiles and the whole position grows more complicated every day.

Existing Early Warning radar chains give an adequate warning of the approach of long-range bombers, whether piloted or robot-controlled: a detection range of 400 miles would mean 40 minutes warning, ample time to prepare defensive missiles and to get fighters to operational height. The same radar chains, even if they could detect a 4,000-mile-distant rocket leaving its site, would only serve to give a twenty-minute precognition of disaster, since interception is not possible. The I.C.B.M. with a thermonuclear warhead constitutes the Ultimate Weapon.

However, a push-button war would annihilate or irreparably cripple both sides, so that, excepting a madman's gesture, the use of the Ultimate Weapon is confined to two conditions:

(*i*) When it is possible to neutralise all the enemy launching sites before they can retaliate;

(*ii*) When the aggressor also possesses defence missiles which are infallibly capable of intercepting retaliatory missiles or aircraft.

The combination of the thermonuclear I.C.B.M. with an infallible anti-missile defence, constitutes the Ultimate Weapons System. At present there are several missing elements in the design of an Ultimate Weapons System, notably the absence of sufficiently accurate guidance for the I.C.B.M., and the absence of any effective homing device for the anti-missile missile.

As an example of the source of guidance application for which celestial radio might be suitable, there is the American Atlas Rocket. This is an I.C.B.M. stated to have a maximum velocity greater than a Mach number of 15, and to be one of the first missiles employing celestial navigation. Details have not been published, but the missile uses a photoelectric eye and a built-in "memory" of star patterns. For the radio-stellar analogue, the guidance mechanism might incorporate a magnetic tape recording of the sequence of radio noise patterns which the antennae should pick up if the missile is accurately on course. This recording could be continuously compared with the actual signals received and any differences used to generate error-signals which, in turn, would actuate the steering servo-mechanisms. The design of such a guidance system is complicated by the changes in the radio noise patterns which may occur when the rocket passes through the ionosphere, and considerable preliminary research will be needed to establish the radio wavelengths which are least affected. The Northrop Snark, an I.R.B.M. now in mass production for the U.S. Strategic Air Command, is another missile using stellar guidance.

A guidance system of the form described makes use of the known relationship between the constellations and any point on the surface of the Earth at a given time: it is therefore completely unaffected by attempts to camouflage the target. It is not suitable for anti-missile missiles, since the spatio-temporal relationship between the missile to be intercepted and any fixed frame of reference is not known to the defence.

RADIO "JAMMING"

It is well known that fighter pilots like to attack when possible "out of the Sun," taking advantage of the Sun's glare to dazzle the enemy. A radio version of this stratagem now appears to be possible, particularly during sunspot maxima or at the time of a solar flare.

Early in 1942, the Early Warning radar chain in England was one day alerted by a barrage of intensely powerful radio noise. Many observers believed this to be jamming of a new kind, possibly the prelude to some mass attack. The interference lasted for two whole days, but the source was not discovered. Eventually, scientists who had been carefully studying the reports and records concluded that, beyond all doubt, the interference originated from the Sun. With the passing of a large sunspot, the interference also disappeared.

Two years earlier an intense magnetic storm had produced world-wide disturbances; Short-Wave radio communication was completely cut-off for many hours, and breakdowns occurred on many other communications networks; even power lines were affected.

Recently, a review of the records of solar radio outbursts has suggested that it may be feasible to

predict solar flares by a margin of some hours, although it is not at present possible to state the exact time when a flare will occur. This suggests the possibility of an attack by enemy aircraft or missiles being launched during a solar outburst which would provide a shield against radar detection. The duration of a flare is quite short, normally about 45 minutes for a large flare, but a bomber fleet, which is standing in readiness, could become airborne and fly several hundred miles towards its target in this time. The possibility of rockets flying "out of the sun" beneath a shield of solar static is rather remote.

COMMUNICATION BY METEOR TRAILS: THE JANET SYSTEM

In the immediate post-war period much research was done on long-range communications with a view to improving reliability, and the general tendency was for the use of higher frequencies. The first of the very high frequency systems was known as Ionospheric Forward Scatter, and employed frequencies of 30 to 50 Mc./sec. beamed towards the ionosphere: the signal was received up to 1,000 miles away after reflection in the E-layer.

The Ionospheric Forward Scatter system differs from a single-hop high frequency system in that, whereas for the latter the normal ionisation level is sufficient to refract the waves back to Earth, for frequencies above 30 Mc./sec. the ion density is insufficient to cause adequate refraction, and normally these frequencies cannot be used for communication beyond optical distances. It had been known for a long time, however, that sporadic V.H.F. signals could be received, and these were assumed to be due to scattering in the ionosphere; subsequent research on narrow-beam high-power transmission led to the development of the Ionospheric Scatter systems.

Early in the development of these systems, signals of extraordinary strength were received in Ottawa from the United States Radio Physics Laboratory, and it was concluded that these were due to reflection from ionised meteor trails. The signals were so powerful that it appeared to be possible to design a low-power long-range communication system based upon the phenomenon. The project was called "Janet," after the god "Janus," who was usually depicted as looking both ways at once. In 1954, Ferranti Electric Company at Toronto began the development of equipment to provide a duplex 60 words per minute teletype channel to operate over the 650 miles between Ottawa and Port Arthur.

It was anticipated that over a 24-hour period communication by way of meteor trails would be possible for 5 per cent of the time, and to achieve the required average of 60 words per minute a sending rate of 1,200 words per minute would be needed during the transmission periods. It was arranged for the incoming teleprinter message to be converted to punched paper tape by a pre-perforator, and stored to await transmission. When the signal strength is adequate, the information channel automatically starts up, the stored tape is read at 120 characters per second by a high-speed photoelectric reader and transmitted. At the same time, the incoming message is detected and converted to a suitable form for writing on 5 of the 6 channels of a magnetic tape. This tape is stored and subsequently read at 60 words per minute to produce a teleprinter line signal. The R.F. carriers in this system have a frequency of 40 Mc./sec. and a separation between channels of 1 Mc./sec.: they are radiated continuously by both terminals being modulated by a 1,300 c./sec. timing signal. The occurrence of a suitable meteor trail causes the receivers at both ends to operate the carrier detectors. The detection of carrier opens a tone gate which allows a 650 c./sec. signal to modulate the transmitters. The gate, which allows information to be passed, opens only when a sufficiently strong 650 c./sec. signal is received.

Over the past 18 months a 600 mile link has been operated with a radiated carrier power of 500 watts, and operating the system when the R.F. signal-to-noise ratio exceeds 12 db. The results are stated to compare favourably with a normal high-frequency teleprinter circuit, with the advantage that the Janet transmission frequency is fixed and does not have to be changed as the ionospheric conditions vary. In addition, interference from Aurora Borealis, sporadic E layer effects, magnetic storms and other sources, does not produce the "blackouts" which are common on normal H.F. systems.

The Calculation of Solar Radiation Intensity from Thermodynamical Theory

To decide upon the most suitable means for detecting Q-band solar energy, and of using the signal to provide an automatic tracking facility, it is first necessary to obtain an estimate of the signal power which will be available. To simplify the initial calculations, certain assumptions will be made:—

(*i*) That the antenna system is matched.

(*ii*) That the antenna beamwidth is equal to the angle subtended by the photosphere.

(*iii*) That the angular diameter of the Sun at a wavelength of 8·6 mm. is equal to the optical diameter.

(*iv*) That the Q-Band radiation is part of the "black-body" radiation from the Sun, and that its magnitude can be calculated from thermodynamical theory.

(*v*) That the attenuation of the radiation during its transmission through the Earth's atmosphere can be calculated from the known atmospheric attenuation at low altitudes.

(*vi*) That a wavelength of 8·6 mm. and a bandwidth of one megacycle are suitable values to consider.

DERIVATION OF THE PROBABLE SIGNAL INTENSITY, NEGLECTING ATMOSPHERIC ATTENUATION

Planck's Radiation Law states that the emissive power $E\lambda d\lambda$ in the range $d\lambda$ of unpolarised radiation per unit surface area, emitted in all directions by a body

Height Km	*Pressure mm.Hg*	*Temp. °K*	*Density ρ gm.cm⁻³*	*Water Vapour Pressure at R.H. 60% mm.Hg*	*Attenuation due to Oxygen*	*Attenuation due to Water Vapour*	*Sum of Attenuations per Km*
0	760	288	$1{\cdot}22\times10^{-3}$	7·67	$7{\cdot}5\times10^{-2}$ *dbKm*$^{-1}$	$9{\cdot}0\times10^{-2}$ *dbKm*$^{-1}$	$1{\cdot}65\times10^{-1}$
1	674	281	$1{\cdot}11\times10^{-3}$	6·6	$5{\cdot}9\times10^{-2}$	$7{\cdot}75\times10^{-2}$	$1{\cdot}365\times10^{-1}$
2	596	275	$1{\cdot}01\times10^{-3}$	4·2	$4{\cdot}6\times10^{-2}$	$4{\cdot}91\times10^{-2}$	$9{\cdot}5\times10^{-2}$
3	525	268	$9{\cdot}1\times10^{-4}$	2·4	$3{\cdot}6\times10^{-2}$	$2{\cdot}8\times10^{-2}$	$6{\cdot}4\times10^{-2}$
4	462	262	$8{\cdot}2\times10^{-4}$	1·44	$2{\cdot}75\times10^{-2}$	$1{\cdot}7\times10^{-2}$	$4{\cdot}45\times10^{-2}$
5	405	255	$7{\cdot}4\times10^{-4}$	$7{\cdot}8\times10^{-1}$	$2{\cdot}13\times10^{-2}$	$9{\cdot}1\times10^{-3}$	$3{\cdot}04\times10^{-2}$
10	198	223	$4{\cdot}1\times10^{-4}$	3×10^{-2}	$5{\cdot}1\times10^{-3}$	$3{\cdot}5\times10^{-3}$	$5{\cdot}45\times10^{-3}$
15	91	214	$1{\cdot}93\times10^{-4}$	$1{\cdot}2\times10^{-2}$	$1{\cdot}08\times10^{-3}$	$1{\cdot}4\times10^{-3}$	$1{\cdot}22\times10^{-3}$
20	42	214	$8{\cdot}9\times10^{-5}$	$1{\cdot}2\times10^{-2}$	$2{\cdot}28\times10^{-4}$	$1{\cdot}4\times10^{-3}$	$3{\cdot}68\times10^{-3}$

FIGURE 2. VARIATION OF ATMOSPHERIC ATTENUATION WITH ALTITUDE.

at $T°$ Absolute, is given by

$$E\lambda d\lambda = \frac{2hC^2}{10^7\lambda^5}\left[\frac{1}{e^{hC/\lambda Tk}-1}\right] \text{ watt./cm.}^2 \quad . \quad (1)$$

where h Planck's Constant $= 6{\cdot}6237\times10^{-27}$ erg.sec.
C velocity of light $= 2{\cdot}9972\times10^{10}$ cm./sec.
k Boltzmann Constant $= 1{\cdot}380\times10^{-16}$ erg./deg.
λ mid-band wavelength in cm.

The temperature of the Sun's surface is estimated at various values according to the method used, but for the purpose of the present calculation it may be taken as 5,785°K.

At a wavelength of 0·86 cm.. the value of $d\lambda$ for a bandwidth of one megacycle is given by

$$d\lambda = \frac{\lambda^2}{C}\times10^6 = \frac{0{\cdot}86^2}{2{\cdot}998}\times10^{-4} = 2{\cdot}465\times10^{-5} \text{ cm.} \quad (2)$$

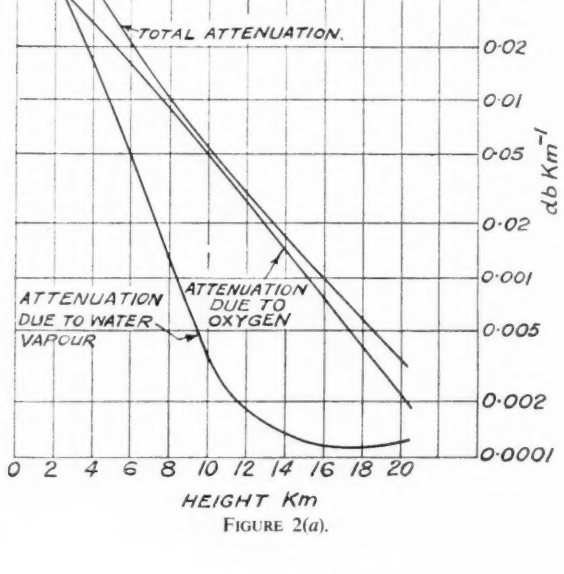

FIGURE 2(*a*).

The Planck law applies for all values of T, but it is a very inconvenient expression to use, and therefore approximate forms of it are widely used.

If λT is less than 0·3 cm. deg., the denominator $(e^{hC/\lambda Tk}-1)$ takes the large value of 119, and therefore an error of less than one per cent results from writing the equation

$$E\lambda d\lambda = \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T}} \quad . \quad . \quad . \quad (3)$$

where $C_1 = 3{\cdot}732\times10^{-12}$ watt. cm.^{2}
$C_2 = 1{\cdot}436$ cm. deg.

This is the Wien distribution law, which chronologically preceded the Planck law. It applies in the visible spectrum ($\lambda < 0{\cdot}7\mu$) for temperatures up to 4,000°K.

If λT is large, $C_2/\lambda T$ is small, and the denominator of equation (1) can be expanded and the equation rewritten as

$$E\lambda d\lambda = \frac{C_1}{\lambda^5}\frac{1}{1+(C_2/\lambda T-1)} = \frac{C_1}{C_2}\frac{T}{\lambda^4} \quad . \quad (4)$$

This is the Rayleigh-Jeans equation. It is accurate to within one per cent for $\lambda T > 77$ cm. deg. Thus for a 6,000° source, it is valid for $\lambda > 0{\cdot}013$ cm.

Equation (4) applies, therefore, to the present problem, and taking C_1/C_2 as $2{\cdot}598\times10^{-12}$ watt. cm. deg.$^{-1}$, we then have

$$E\lambda d\lambda = \frac{2{\cdot}598\times10^{-12}\times5785}{(0{\cdot}86)^4}\times2{\cdot}465\times10^{-5}$$
$$= 6{\cdot}75\times10^{-13} \text{ watt./cm.}^2\text{/Mc./sec.} \quad (5)$$

Neglecting, for the present, the effect of any atmospheric attenuation, the power per unit area per megacycle bandwidth at the Earth's surface is given by

$$W = E\lambda d\lambda\left[\frac{\text{Sun's radius}}{\text{Earth's solar distance}}\right]^2 \quad . \quad (6)$$
$$= 6{\cdot}75\times10^{-13}\left[\frac{6{\cdot}96\times10^{10}}{1{\cdot}496\times10^{13}}\right]^2$$
$$= 6{\cdot}75\times10^{-13}\times2{\cdot}15\times10^{-5}$$
$$= 1{\cdot}45\times10^{-17} \text{ watt./cm.}^2\text{/Mc./sec.} \quad . \quad (7)$$

CORRECTION OF PROBABLE SIGNAL INTENSITY FOR ATMOSPHERIC ATTENUATION

The attenuation of 8·6 mm. radiation in an atmosphere which is one fifth oxygen, at a total pressure of 760 mm. of mercury, is given as about 0·05 db./km.* The attenuation due to water vapour is given as about 0·08 db./km. for 10 gm./m.^{3} of water vapour (66 per cent R.H. at 18°C). The attenuation due to water vapour is roughly proportional to the absolute humidity, and the oxygen attenuation varies as the square of the pressure.

Figure 2 and 2(*a*) show the variation of attenuation with altitude.

These figures assume that the radiation is falling perpendicularly upon the Earth's surface, but even if the angle of incidence were such as to double the total path length, it is apparent that the total attenuation in a clear atmosphere is less than 1 db. A sufficient allowance for atmospheric attenuation will have been made if equation (7) is amended to

$$W = 10^{-17} \text{ watt./cm.}^2\text{/Mc./sec.} \quad . \quad (8)$$

As an interesting check upon the accuracy of the foregoing theoretical analysis, it may be noted that the value for actual received intensity of radiation at a wavelength of 6 mm. (Table III has been given† as

$$3{\cdot}4 \times 10^{-19} \text{ watt./m.}^2\text{/c./sec.}$$
$$= 3{\cdot}4 \times 10^{-17} \text{ watt./cm.}^2\text{/Mc./sec.} \quad . \quad (9)$$

which may be regarded as satisfactory agreement.

CALCULATION OF EFFECTIVE APERTURE OF ANTENNA

The most effective antenna to use is a uniformly illuminated paraboloid, for in this case its receiving aperture is equal to its actual aperture. For any other type of illumination the effective aperture is less than the actual aperture, the only advantage being that the sidelobes may be decreased. However, for uniform illumination the intensity of the first sidelobe is only 1·75 per cent of the main maximum‡, which is sufficiently good for the present purpose. It can be shown that for a uniformly illuminated paraboloid, the half-power width θ in degrees is given by

$$\theta = 1{\cdot}87\lambda/D \quad . \quad . \quad . \quad (10)$$

where λ is the wavelength in cms., and D is the diameter of the paraboloid in feet.

The angular diameter of the Sun is $\frac{1}{2}$ degree, and the mean wavelength of the radiation is to be taken as 0·86 cm.; therefore:

$$D = 1{\cdot}87\,\frac{\lambda}{\theta} = \frac{1{\cdot}87 \times 0{\cdot}86}{0{\cdot}5} = 3{\cdot}2 \text{ ft.} \quad . \quad (11)$$

This is the diameter of paraboloid required to give a beam equal in angle to the Sun's angular diameter. It is evident that a standard 3 ft. paraboloid could be used, the actual aperture of which is given by

$$A = \frac{\pi D^2}{4} = 7{\cdot}1 \text{ ft.}^2 \quad . \quad . \quad . \quad . \quad (12)$$

Since uniform illumination is difficult to achieve in practice, the effective aperture will be less than this, 60 per cent being a probable value. Then:

$$A_{\text{eff}} = 4{\cdot}26 \text{ ft.}^2 = 3{\cdot}95 \times 10^3 \text{ cm.}^2 \quad . \quad . \quad (13)$$

CALCULATION OF PROBABLE SIGNAL/NOISE RATIO IN RECEIVER

The power per megacycle bandwidth of received radiation at the antenna is given by

$$P = W \times A_{\text{eff}}. \quad . \quad . \quad . \quad (14)$$

Where W = incident radiation intensity
$= 10^{-17}$ watt./cm.^{2}/Mc./sec. and
A_{eff} = effective aperture of paraboloid
$= 3{\cdot}95 \times 10^3$ cm.^{2}

Then combining these values:

$$P = 10^{-17} \times 4 \times 10^3 = 4 \times 10^{-14} \text{ watt./Mc./sec.} \quad (15)$$

Assuming that the antenna is matched, then the maximum noise power at the input to a perfectly noiseless receiver system (receiver system here includes local oscillator and crystal mixer) is given by*

$$P_n = kT\Delta f \text{ ergs.} \quad . \quad . \quad . \quad (16)$$

where k = Boltzmann's constant, T = ambient temperature, say 300° Absolute. So that, over a bandwidth Δf of one megacycle;

$$P_n = 1{\cdot}380 \times 10^{-16} \times 300 \times 10^6 \text{ ergs.}$$
$$= 4{\cdot}14 \times 10^{-15} \text{ watt.} \quad . \quad (17)$$

The probable level of the Q-Band signal from the Sun above the thermal noise is therefore

$$\frac{4 \times 10^{-14}}{4{\cdot}14 \times 10^{-15}} = 10 \text{ db.} \quad . \quad . \quad (18)$$

This figure is based on the unpolarised radiation from the Sun. If an ordinary parabolic aerial is used, only one polarisation will be received, and therefore the signal will be down by 3 db. Also, the receiver noise level will be about another 17 db., giving a final estimated value for the level of Q-band noise below "background" noise of 10 db.

However, if a superheterodyne receiver is used, there will be two bands of frequencies, above and below the frequency of the local oscillator, which will beat with the latter to produce the required intermediate frequency.

Hence, in calculating the radio power received from the Sun, the bandwidth of solar energy contributing to the output of the second detector will be twice the bandwidth of the intermediate frequency amplifier.

Standard Techniques of Measuring Extra-Terrestrial Radio Waves

Extra-terrestrial radio sources are of a non-coherent nature; and the receiver output due to them will be indistinguishable from the internally generated receiver noise. It follows, therefore, that methods employed for obtaining receiver noise figures should be equally suitable for measuring received radio power.

*L. N. Ridenour, *Radar System Engineering*[209], p. 60, 1947.
†*Astrophysical Quantities*, C. W. Allen, p. 153, Athlone Press, 1955.
‡Pollard and Sturtevant, *Microwaves and Radar Electronics*, 1948.
**Noise in Microwave Receiver Crystal Systems Microwave Receivers*, Van Voorhis Radiation Series, No. 23, McGraw-Hill.

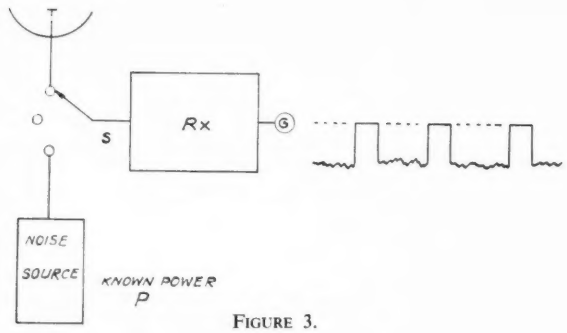

FIGURE 3.

In Fig. 3, if the switch *S* is placed in its intermediate position, the receiver output will be due to its own noise and a galvanometer reading, i_1, will be obtained. If the noise source of known power is connected to the receiver, the galvanometer current will increase to i_2: and from the ratio i_2: i_1 and the noise power source, the noise figure for the receiver may be obtained. When the aerial is connected instead of the noise source, a third reading i_3 is obtained, and the ratio $i_3 : i_2$ may be employed to calculate the aerial signal power.

If the switch is mechanically driven to connect either the noise source or the aerial to the receiver input, we obtain a record as in Fig. 5. Here, the receiver is being continuously monitored, and fluctuations in gain will affect equally the signal output and that due to the noise source.

However, this device requires a recorded output which must be interpreted to ascertain the aerial power. An improvement is due to Dicke, whose radiometer is depicted in Fig. 8.

It may be seen that besides switching the receiver input, the receiver output is also switched at the same time. The galvanometer reading is then the difference between the two readings which the aerial or the noise source alone would give. The switching should be sufficiently rapid so that it may be assumed that the gain does not vary during a complete switching cycle. If the noise source is then adjusted so that the receiver output is precisely equal to that obtained when the aerial is connected but with no incoming signal, then no galvanometer reading will be obtained. When a signal is received, the galvanometer reading will be due to it alone and, knowing the receiver noise figure, its power may be calculated. The device is insensitive to gain fluctuations of a period long compared with the switching frequency.

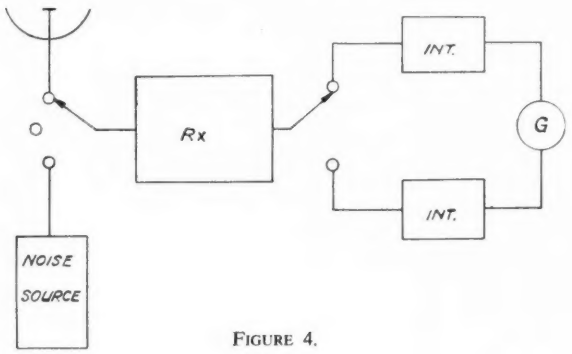

FIGURE 4.

Besides detecting the signal, a knowledge of its position is required. To obtain this, a directional aerial may be used; maximum received signal indicating that the aerial is pointing towards the source, in a manner analogous to an optical telescope. Unfortunately, the radio wavelengths are vastly longer than those of visible light and the beamwidth of the radio telescope will be much wider than its optical counterpart. This leads to doubt as to when the radio telescope is pointing towards the source, and the accuracy of the bearing deteriorates accordingly.

This may be overcome to some extent by using the split-beam technique. This consists of two aerials for each plane, whose polar diagrams are slightly displaced from each other, so that when maximum signal is received by one aerial, something below maximum is received by the other. Because the sloping "sides" of the polar diagram are employed rather than the fairly flat "top," the change of received signal with varying angle is much more rapid. When the signals from the aerials are equal, the composite aerial points towards the source. Such an aerial is useful for automatically tracking a target, as it also gives the sense of the error, *i.e.* whether the aerial is pointing to the left or right of the wanted direction. The penalty paid is that, due to the offset, the aerials no longer give maximum signal in the direction of the target and, as the angle between them is increased to give greater bearing sensitivity, so the gain of the system diminishes.

However, none of the aerials discussed is capable of great accuracy without being at the same time of enormous size. A third method is therefore used which again has its optical counterpart—that of interferometry. This method also employs two aerials, but instead of working on the amplitudes, it employs the relative phases of the signals. The phase of the signal

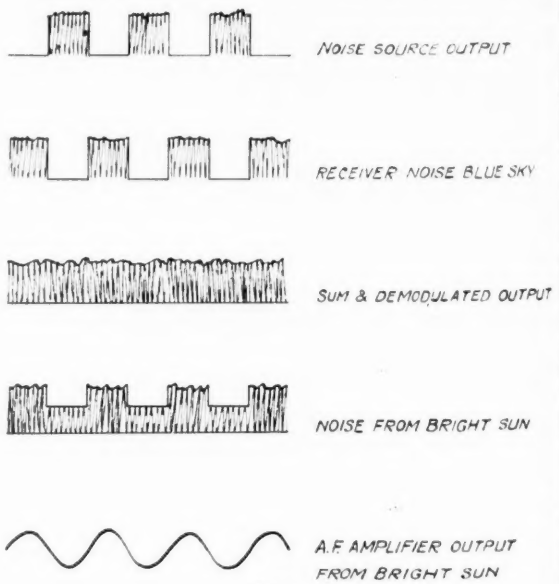

FIGURE 5.

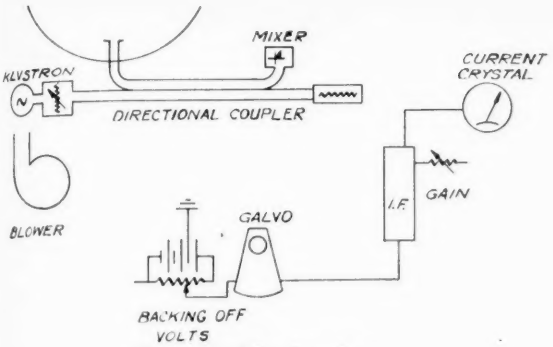

FIGURE 6. Q-band receiver.

will depend on the path length between the source and the aerial. If the path lengths from source to each aerial are equal or differ by n, where n is an integer, then the signals will be in phase: if they differ by $\frac{1}{2}m$, where m is equal to 1, 3, 5, 7, . . . and so on, they will be in anti-phase. It is clear that there will be many positions which the source can occupy relative to the aerials, to give similar phase characteristics, and some means is necessary to resolve the ambiguities. If it is assumed that the relative phase is measured at a point mid-way between the aerials, then it is clear that one possible method is to move the aerials by an equal distance away from, or toward, this mid-point. Only if the path lengths are equal will the relative phase be unchanged, and this implies that the source lies along the normal passing through the mid-point of the line joining the two aerials. Such a system is capable of great accuracy while employing aerials of relatively wide beamwidth.

The Experiments of Kelvin Hughes

This work was done mainly to attempt to confirm the theoretical Q-Band radiation from the Sun; and to verify the almost negligible calculated attenuation caused by its passage through the Earth's atmosphere.

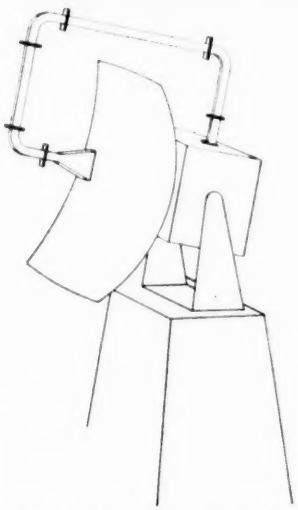

FIGURE 7. Q-band feed to parabola.

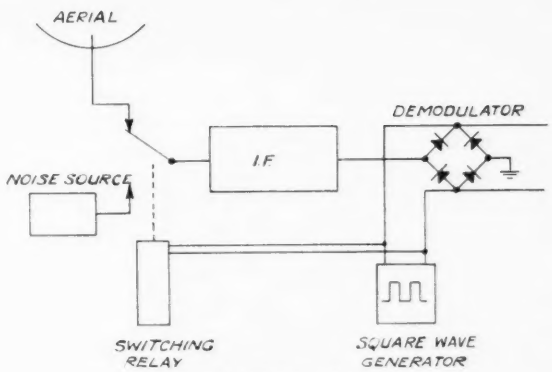

FIGURE 8. Dicke radiometer.

A parabolic dish of some three feet aperture for use in X-band being available, this was pressed into use; a small Q-band horn being placed at the focus, with a waveguide run to the R.F. head. The suitably attenuated output from a VX5023T klystron was fed through a directive feed to the mixer, the output from which formed the input to a standard intermediate frequency amplifier of some 1·8 Mc./sec. bandwidth. The second detector current of the amplifier was monitored by a suitable mirror galvanometer; means being provided for backing off the standing current of the diode detector. Fig. 6 shows the arrangement.

At a later date, this apparatus was trunnion-mounted so that the aerial could be directed towards the Sun instead of having to wait for the Sun to transit the aerial. (Fig. 7.)

After some initial measurements had been made, which demonstrated that the energy from the Sun was readily perceptible, a refinement was added in the shape of a Dicke radiometer, employing electronic switching in the first stage of the intermediate frequency amplifier. (Figs. 8 and 9.)

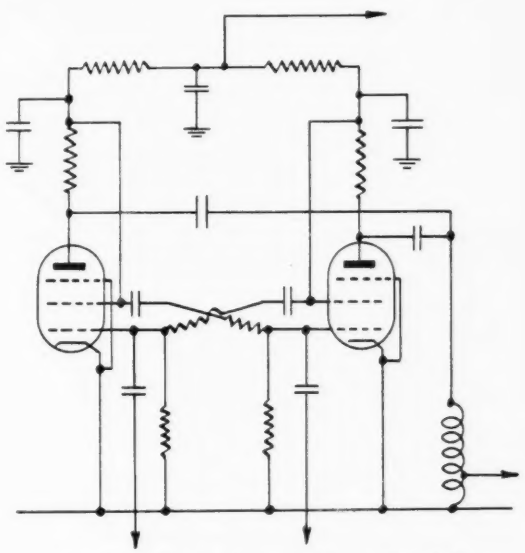

FIGURE 9. Dicke radiometer—electronic switch.

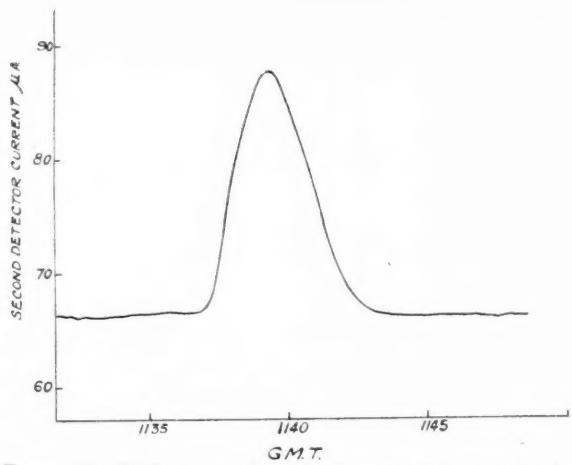

FIGURE 10. Radio energy from the sun. Q-band wavelength 8 mm. 6th September 1957.

This somewhat inelegant apparatus enabled an assessment of the problem to be made.

A rough check of the available power at the aerial was made as follows:—

I.F. gain—(taking into account conversion loss)	58 db.
Effective aerial aperture	0·5 m.²
Equivalent rectangular receiver bandwidth	2 Mc./sec.
Increase in 2nd detector current due to power from the Sun	20 μA

The power at the 2nd detector due to the Sun is $i^2r = 20^2 \times 10^{-12} \times 220 = 8{\cdot}8 \times 10^{-8}$ watt.

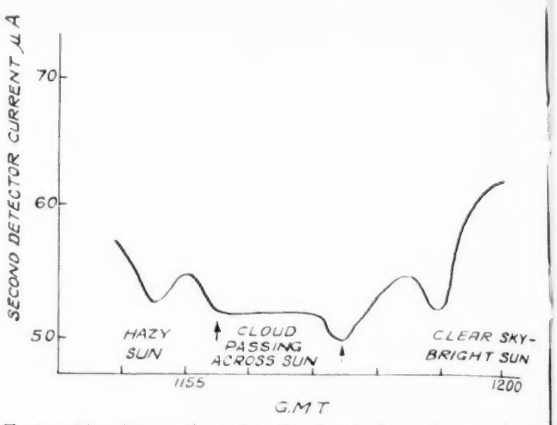

FIGURE 11. Attenuation of radio signals from the sun due to the passage of clouds across it. Q-band wavelength 8 mm. 6th September 1957.

Dividing this by the receiver gain, we arrive at the power delivered by the aerial:

$$\frac{8{\cdot}8 \times 10^{-8}}{10^{5{\cdot}8}} \text{ watt.}$$

This quantity is further divided by the aerial aperture and the receiver bandwidth:

$$\text{Received power from Sun} = \frac{8{\cdot}8 \times 10^{-8}}{10^{5{\cdot}8} \times 5 \times 10^{6} \times 2}$$

$$= 1{\cdot}4 \times 10^{-17} \text{ watt./cm.}^2\text{/Mc./sec.}$$

which is of the right order of magnitude.

Figure 10 is a record obtained from the simple set-up depicted in Fig. 6 as the Sun transits the aerial, while Fig. 11 shows the attenuating effect of heavy

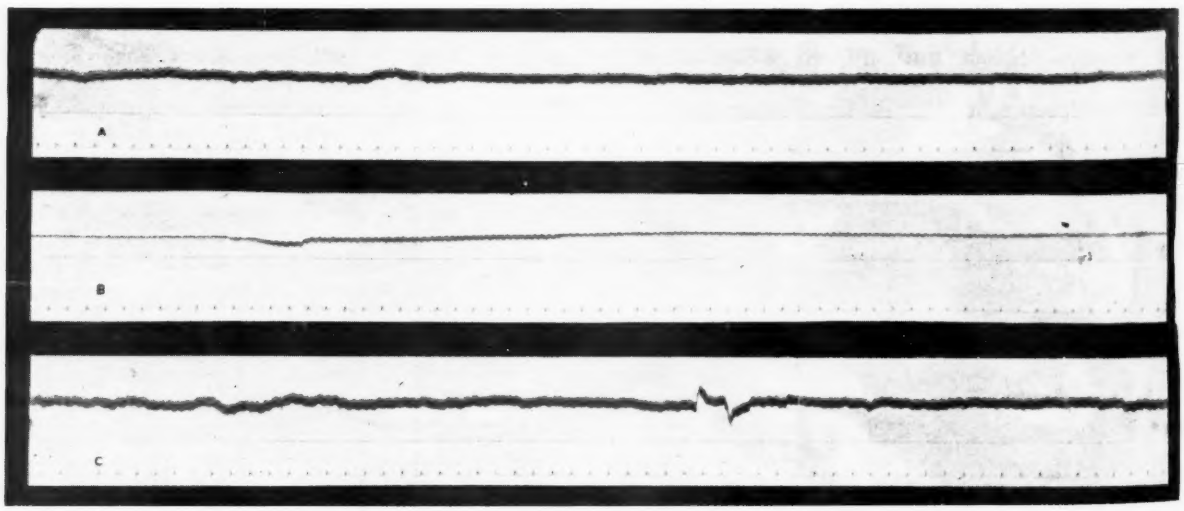

FIGURE 12.

A. Portion of a typical daily record. The signal amplitude is about 1 volt. (15th October 1957.)

B. The result of interposing a Bridged-T narrow-band amplifier in an attempt to improve the signal/noise ratio so that lock-follow servos might be added. (18th October 1957.)

C. A record taken on 15th October 1957, a few hours after (A), through heavy cloud patches.

cumulus clouds passing across the Sun when the aerial is manually tracked to maintain maximal signal. It is obvious that the reduction of signal is not serious. Fig. 12 reproduces some of the automatic pen recordings taken at Dunmow during October 1957. In each case the marker pips are at one second intervals, and the thin straight line represents the base level obtained by setting up against a clear sky.

These experiments show that, using simple and inexpensive apparatus,' ample power may be received from the solar Q-Band radiation to operate an automatic tracking device. The close agreement between the received signal strength and that predicted from thermodynamical theory, employing Planck's equation or its derivatives, and the calculable attenuation due to atmospheric constituents, is most satisfactory, as it demonstrates that a purely theoretical basis is adequate for the design of apparatus intended to operate by means of radio waves originating from the Sun or other Celestial thermal sources.

It may be concluded that no serious difficulties are likely to occur in the design of practical Solar Radio Sextants, either for military or commercial applications, since both the theory and the techniques are known.

The principal missing factor in the design of a production model Radio Sextant is an adequate knowledge of the variation in attenuation under all weather conditions and at different angles of elevation. For a thorough investigation, an equatorially mounted Q-band receiver has been set up at Dunmow with a synchronous electric drive to provide accurate tracking of the Sun. The receiver is calibrated against a standard noise source and the output fed to a paper recorder. The records obtained over a period of some months will be correlated with the data from nearby Meteorological Stations and, it is hoped, will constitute a useful addition to knowledge of the atmospheric attenuation of millimetre waves.

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Finally, the author is particularly grateful to Arthur J. Hughes, O.B.E., F.R.Ae.S., who initiated the work described and who suggested that this report be written. Some of the material will be included in a book on the history of astro-navigation which is to be published by Chapman and Hall.

APPENDIX I

ASTROPHYSICAL DATA AND PHYSICAL CONSTANTS

Astronomical Unit (mean Earth-Sun distance)	A.U. $= 1{\cdot}496 \times 10^{13}$ cm.
Parsec—Distance of star whose parallax is one second	pc. $= 3{\cdot}0857 \times 10^{18}$ cm. $= 206,265$ A.U. $= 3{\cdot}262$ light years
Light year—Distance light travels in one terrestrial year	ly. $= 9{\cdot}4605 \times 10^{17}$ cm. $= 6{\cdot}324 \times 10^{4}$ A.U.
Light-time for 1 A.U.	$= 499{\cdot}01$ secs.
Solar Mass	$M_0 = 1{\cdot}991 \times 10^{33}$ gm.
Solar Radius	$R_0 = 6{\cdot}960 \times 10^{10}$ cm.
Solar Volume	$V_0 = 1{\cdot}412 \times 10^{33}$ cm^3.
Solar Surface Area	$= 6{\cdot}087 \times 10^{22}$ cm.^{2}
Effective Solar Temperature	$T_e = 5785°$ Abs.
Solar Radiation	$L_0 = 3{\cdot}86 \times 10^{33}$ erg./sec. $= 3{\cdot}86 \times 10^{26}$ watt.
Earth Mass	$M_E = 5{\cdot}977 \times 10^{27}$ gm.
Earth Mean Radius	$R_E = 6{\cdot}37 \times 10^{8}$ cm.
Earth-Moon mean distance	$= 3{\cdot}844 \times 10^{10}$ cm.
Moon Radius	$R_M = 1{\cdot}738 \times 10^{8}$ cm.
Velocity of Light	$c = 2{\cdot}9979 \times 10^{10}$ cm./sec.
Planck Constant	$h = 6{\cdot}6237 \times 10^{-27}$ erg. sec.
Boltzmann Constant	$k = 1{\cdot}38 \times 10^{-16}$ erg./deg.
Stefan-Boltzmann Constant	$\sigma = 5{\cdot}6698 \times 10^{-5}$ erg./cm.^{2}/deg.^{4}/sec. $= 5{\cdot}6698 \times 10^{-12}$ watt./cm.^{2}/deg.^{4}
First Radiation Constant (emittance)	$= 2hc^2$ $c_1 = 3{\cdot}74 \times 10^{-5}$ erg./cm.^{2}/sec.
First Radiation Constant (radiation density)	$= 8hc$ $c_1 = 4{\cdot}990 \times 10^{-15}$ erg. cm.
Second Radiation Constant	$= hck$ $c_2 = 1{\cdot}43868$ cm. deg.
Wein displacement law constant	$= c_2/4{\cdot}965 = 0{\cdot}28976$ cm. deg.
Radio Emission Flux Unit	F.U. $= 10^{-22}$ watt./m.^{2}/c./sec.

(With acknowledgments to C. W. Allen—Astrophysical Quantities (Athlone Press, London, 1955))

APPENDIX II

THE POSSIBLE EFFECTS ON TERRESTRIAL COMMUNICATIONS OF A CLOSE SUPERNOVA

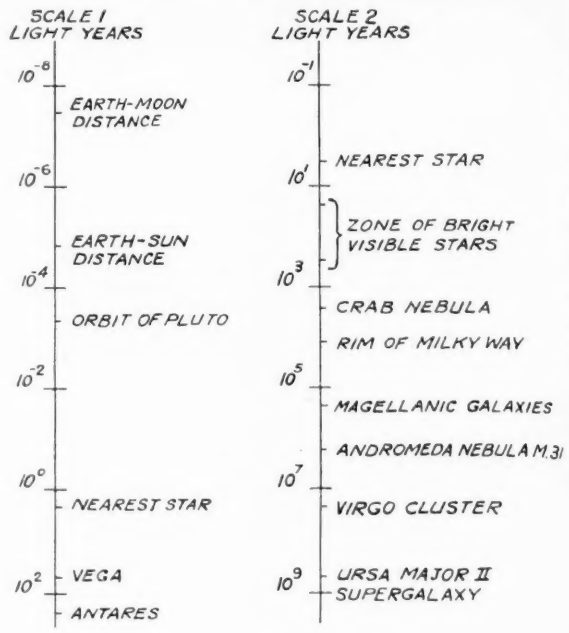
It is instructive to consider what might happen on Earth in the event of a new supernova arising in the solar neighbourhood. This is a remote, but quite definite, possibility, although the implications do not appear to have been considered elsewhere. The matter is of some importance from the viewpoint of Security and Defence, because it is perfectly possible to maintain satisfactory communications in the presence of intense cosmic noise—provided preparations are made in advance.

Novae are variable stars which differ from other types of variable star in that the phenomenon is usually non-recurrent. For reasons which are as yet little understood, a tremendous explosion occurs; within a few days the brightness of the star increases by a factor of 10^4 or 10^5, and simultaneously a gaseous shell is expelled with an enormous velocity (of the order of 1,000 kilometres per second). The power output at maximum is of the order of 10^{31} watt., or about 100,000 times the power output of our own Sun. Among the 10^{11} stars in our own Milky Way Galaxy, Novae brighter than the 9th magnitude occur with a frequency of ten to twenty per annum, and over a hundred have been observed.

Supernovae occur less often than novae, but the observed phenomena are much the same except that the scale is immensely greater: the explosion is far more violent and the peak power output is of the order of 10^{35} watt., which is of the same order as the total power output of our Galaxy. The total energy released may be related to the stellar mass-energy mc^2; the peak output corresponds to a rate-of-loss-of-mass of about 10^{21} grams per second, or the dissipation of a complete solar mass in about 100,000 years. The total energy emitted before the outburst subsides corresponds to about 10^{-5} solar masses, so that in many cases a substantial nucleus remains.

In all, about 50 supernovae have been observed in other galaxies and their frequency of occurrence is estimated at about one in 360 years per galaxy. However, over the past few hundred years two or three supernovae have been observed in each of a number of galaxies, so that the estimated frequency of occurrence must be regarded as only statistically correct. In our own Galaxy there have been four supernovae recorded since the Star of Bethlehem: one in 369 A.D. in Cassiopeia (now the radio source, Cassiopeia A), and one in 1054 in Taurus (now the Crab Nebula), one in 1572 which was observed by Tycho Brahe in Cassiopeia, and one in Ophiuchus which was observed by Johann Kepler in 1604. On the basis of the statistical frequency of occurrence the next one is due in six years time—in 1964.

Suppose that a new supernovae explodes into view at a distance of about four light years from the Sun. This is the distance of the nearest known star, Proxima Centauri, and is therefore the worst possible case. We may calculate the radiation intensity in two different ways, depending upon whether we assume a thermal or a non-thermal model for the source: in fact, it is known that the radiation at radio frequencies from supernovae must be generated by some kind of synchrotron mechanism, since on a thermal basis improbable temperatures would be required—something of the order of 10^{14}°K. Nevertheless, the thermal component must be taken into account, since it will be present whether or not enhanced radiation due to other processes is produced.



THESE SCALES ARE VERY ROUGH APPROXIMATIONS ONLY, ONE LIGHT YEAR IS ABOUT 5,900,000,000,000 MILES

FIGURE 13.

Taking the thermal model first, the solar radiation is $3{\cdot}86 \times 10^{26}$ watt., and the maximum output from a supernova is of the order of 10^9 times as great, that is, 10^{35} watt. Minkowski has calculated that the nucleus of the Crab Nebula is a star with a radius 1/50th that of our Sun, or about $1{\cdot}4 \times 10^9$ cm., its surface area is therefore $2{\cdot}46 \times 10^{19}$ cm.^{2}. At peak output the radiation density was, therefore:—

$$10^{35}/2{\cdot}46 \times 10^{19} = 4{\cdot}06 \times 10^{15} \text{ watt./cm.}^2. \qquad (19)$$

Dividing by the Stefan-Boltzmann constant,

$$4{\cdot}06 \times 10^{15}/5{\cdot}67 \times 10^{-12} = 7{\cdot}17 \times 10^{26}\,°\text{K}^4. \qquad (20)$$

$$\text{Log. } 7{\cdot}17 \times 10^{26} = 26{\cdot}8555. \quad \text{Log. } (7{\cdot}17 \times 10^{26})^{\frac{1}{4}} = 6{\cdot}7079. \quad \text{Antilog.} = 5{\cdot}105 \times 10^6.$$

Temperature of the star at time of maximum power

$$= 5{\cdot}1 \times 10^6\,°\text{K}. \qquad (21)$$

Considering the star as a blackbody radiator, the appropriate formula for the power emitted at a wavelength λ (metres) in the frequency interval $-\Delta f$ is

$$P = \frac{2\pi kT}{\lambda^2}\Delta f \text{ watt./m.}^2. \qquad (22)$$

If the radius of the star is r the blackbody emission from the entire surface is

$$P = \frac{2\pi kT}{\lambda^2}\Delta f.\, 4\pi r^2 \text{ watt.} \qquad (23)$$

and if R is the Earth-star distance (or Sun-star distance, which is virtually the same) the amount received on the Earth will be

$$P_e = \frac{2\pi kT}{\lambda^2}\Delta f.\left(\frac{r}{R}\right)^2 \text{ watt./m.}^2. \qquad (24)$$

If we consider a wavelength of one metre, and take T as $5{\cdot}1 \times 10^6$, we have

$$P_e = 2\pi \times 1{\cdot}38 \times 10^{-23} \times 5{\cdot}1 \times 10^6 \times \left(\frac{1{\cdot}4 \times 10^9}{4000 \times 1{\cdot}496 \times 10^{13}}\right)^2$$

$$= 2{\cdot}4 \times 10^{-31} \text{ watt./m.}^2\text{/c./sec.}$$

$$= 2{\cdot}4 \times 10^{-9} \text{ flux units.} \quad . \quad . \quad . \quad (25)$$

From this it is clear that the thermal component of radiation received on Earth would be indetectable at radio wavelengths.

Taking now the non-thermal model, the radiation from a supernova at 4 light years distance would be 10^6 times as great as that from one at 4,000 light years, which is the distance of the Crab Nebula. If we assume that the ratio of optical emission to radio emission is constant for a given supernova*, then since the 1054 A.D. star was about 3,000 times brighter at its maximum than its remnant is now, we obtain a ratio of $3 \times 10^9 : 1$ for the radiation intensity of the new supernova compared with the Crab Nebula. This amounts to about 5×10^8 flux units at 100 Mc./sec. or about $2{\cdot}6 \times 10^8$ as much as solar radiation at the same wavelength.

Expressing this as watt./m.^{2} for a 10 megacycle bandwidth and one square metre effective receiving area, we obtain: —

Power from supernova at 4 light years distance

$$= 5 \times 10^{-7} \text{ watt.} \quad . \quad (26)$$

This may now be compared with the order of signal strength encountered in normal radar practice. The radar equation

$$P_r = \frac{P_t G A e S}{16\pi^2 R^4}$$

gives the power received by a radar aerial in terms of the power transmitted, the aerial gain, the effective aerial aperture, the target area and the range. Some everyday values would be: $P_t = 50$ kilowatts; $G = 1{,}000$; $A = 0{\cdot}1$ m.^{2}. The bandwidth would be of the order of 10 Mc./sec.

For a medium-sized merchant vessel (echoing area about 8,000 metres^2) at a range of 20,000 metres (about 12 miles), the returned signal strength is approximately 5×10^{-10} watts or 5×10^{-9} watt./m.^{2}.

For the case of a medium-sized bombing aircraft (equivalent echoing area about 40 metres^2) at a range of 20,000 metres, the returned signal strength is approximately 2×10^{-12} watts or 2×10^{-11} watt./m.^{2}.

It is thus apparent that provided the angular position of the supernova came within the main beam of the aerial system, the background noise due to the new star would exceed medium range marine radar signals by a factor of roughly 100, and would swamp aircraft-tracking radars by a factor of about 25,000.

It may be objected that we have obtained an alarming example by placing the supernova at the distance of the nearest known star, but on the other hand we did not choose a particularly powerful supernova. The diffuse nebular remnant of the 369 A.D. supernova gives a flux intensity at the Earth's surface about twice as great as that from the Crab Nebula, and its estimated distance is about $2\frac{1}{2}$ times as great, hence its actual radiation intensity is about 12 times greater. There is insufficient evidence to give an accurate figure for the amount by which the radiation from this source has declined in over 1,500 years, but a fairly conservative estimate gives a figure of 10^5. So that on this basis we could have a supernova 400 times more powerful than the example given, without departing from known models, and the distance of the new supernova could thus be made 80 light years, within which distance there are many stars available as prospective supernovae.

As for radio communication, the B.B.C. European Service, with a power of 150 kilowatts, gives a range of a little over 600 miles before the field strength falls to 5×10^{-7} watt./m.^{2}; or for a signal 3 db. above the supernova noise, a range of about 400 miles, assuming the noise source to be a 1054 type star at 4 light years. If we imagine the noise source to be the more powerful supernova taken for our second example, and also at a distance of 4 light years, then the range of the European Service falls to no more than 20 miles before it becomes lost in the background noise.

*Which it is according to Mills, Little and Sheridan, *Australian Journal of Physics*, 8, 84.

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TECHNICAL NOTES

A Note on the Effect of Surface Finish on the Thrust of a Supersonic Conical Nozzle

by

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THE PROPELLING NOZZLES tested[1] are turned from brass and the interior surface finish shows a centre line average of about 15 micro inches when examined on a Taylor Hobson machine. This is fairly rough compared with the estimated boundary layer thickness and it was required to know whether this in fact affected the thrust. The thrust of a nozzle manufactured by the usual process was measured before and after a polishing process. An improvement of one half per cent was recorded.

NOTATION

F thrust (lb.)
p_0 reservoir pressure (lb./in.^{2})
s standard deviation (lb.)

METHOD OF POLISHING

The nozzle chosen for examination was of $\frac{1}{2}$ in. diameter throat, area ratio 6·0 and half divergence angle 9°. The entry radius was 1 in. There was a parallel section at the throat of about $\frac{1}{32}$ in. long.

In order to retain the shape of the divergence, a conical plug of 9° half angle was used as a polishing mandrel. The plug was wrapped with a triangular sheet of fine emery paper and the nozzle was rubbed by hand. As well as rotating the plug, the ends of the emery paper were moved longitudinally with the fingers so that a roughly random rubbing effect was produced. The process began with Oakley's Emery Polishing Paper Grade 3 and progressively finer grades were used down to 4/0.

Initial examination on a Taylor Hobson machine gave a centre line average of 14 micro inches and this was eventually reduced to less than 1 micro inch. Fig. 1 is a sample of the traced profile before and after polishing.

EXPERIMENTATION

The thrust measuring apparatus has been described previously (Ref. 2). The nozzle was tested while discharging air at reservoir pressures from 500 to 1,000 lb./in.^{2} Approximately 28 independant observations were made in each case and tests were carried out in random order. In each experiment a second control nozzle was tested.

RESULTS AND CONCLUSIONS

Before polishing, the nozzle thrust was found to be,

$$F = 0{\cdot}307909p_0 - 20{\cdot}68 \text{ (lb.)} \quad . \quad . \quad (1)$$

and $s = \pm 2{\cdot}80$ lb. $(24d/F)$ for a single observation. Thus, the thrust coefficient, $C_F = 0{\cdot}9632$ at the designed reservoir pressure, $p_0 = 928$ lb./in.^{2}

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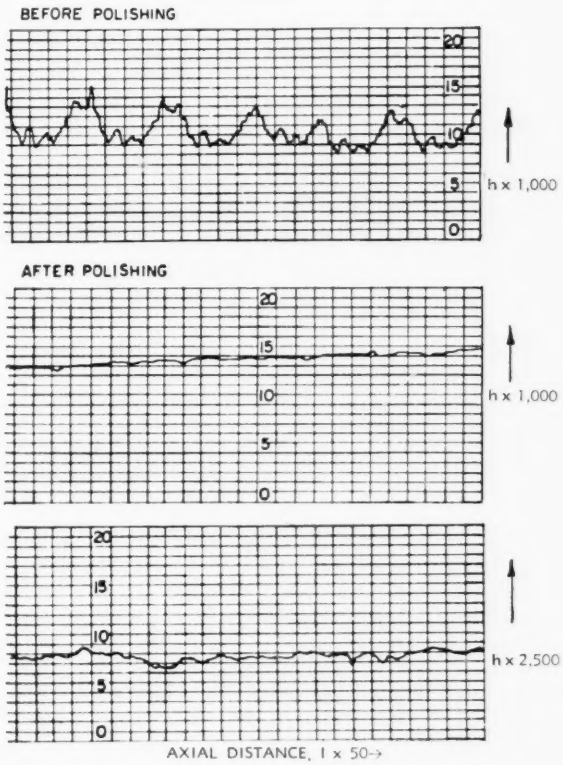

FIGURE 1.

After polishing,

$$F = 0{\cdot}306594p_0 - 18{\cdot}12 \text{ (lb.)} \quad . \quad . \quad (2)$$

and $s = \pm 3{\cdot}06$ lb. $(28d/F)$ for a single observation. This indicates an improvement of 1·34 lb. at $p_0 = 928$ lb./in.^{2} which is significant at the 5 per cent probability level. The improvement in thrust coefficient is 0·0051.

Thus, polishing the nozzle has improved its thrust efficiency by 0·5 per cent.

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Annular Flow—A Note on the Turbulent Velocity Profile

By

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THE IMPORTANT characteristics of the turbulent velocity profile of a plain concentric annulus and some of the methods of correlating the velocity distribution are briefly reviewed. The average velocities in an annular section are examined and some experimental data is correlated by a modified power law.

THE TURBULENT FLOW VELOCITY PROFILE

For an axi-symmetric plain annulus, some of the main features of the experimental terminal velocity profile in fully turbulent flow are as follows:—

(*a*) Unlike that in an open pipe, the profile is asymmetrical.

(*b*) The radius of the maximum velocity r_m is (as far as experimental determination allows) the same as that for laminar flow, given by Lamb[1] as

$$r_m = \sqrt{\left[\frac{r_0^2 - r_1^2}{2\log_e (r_0/r_1)}\right]}$$

(r_0 and r_1 refer to the outer and inner radii of the annulus and r_m is a little less than $\left(\frac{r_0 + r_1}{2}\right)$.

(*c*) According to Rothfus, Monrad and Senecal[2], the two radii for a given velocity in a laminar flow give equal velocities in a turbulent flow, and

(*d*) The average velocity of flow inside r_m is greater than the average velocity outside r_m.

METHODS OF CORRELATING VELOCITY DISTRIBUTION

The experimental velocity data in turbulent flow have been correlated in various ways, examples of which are as follows:—

1. A universal logarithmic profile (for the turbulent zone) of the form

$$U^* = A + B \log_e Y^*$$

Two separate equations are necessary for the inner and outer regions of the annulus, the four constants being determined from the data. U^* and Y^* have their usual meanings, but since the inner and outer wall shears are different, the appropriate friction velocity (and appropriate wall distance) is applied in each region. Knudsen and Katz[3] have used this method and in addition their results indicate that $U^* = Y^*$ in the immediate vicinity of the boundaries as for the case of the open tube.

2. A single universal logarithmic profile which is valid across the whole annular section. This has been devised by Rothfus, Monrad and Senecal, who by using the hydraulic radius concept in the outer region of the section introduced the idea of an "equivalent open-pipe."

They then correlated their turbulent velocity data by using the general logarithmic profile for the open pipe with modified friction velocity and friction distance parameters. The friction velocity for the equivalent pipe system is the same as that for the outer region of the annulus, while the equivalent pipe wall distance to be used in the modified friction distance parameter, Y_E^*, is

$$Y_E = \left(\frac{r_0^2 - r_m^2}{r_0}\right) - \left[\left(\frac{r_0^2 - r_m^2}{r_0}\right)^2 - r_0^2 + r^2 + 2r_m^2 \log_e (r_0/r_1)\right]^{1/2}$$

(This was derived from the theoretical laminar profile equation and the equivalent pipe radius.)

3. Power Laws. These are of the form

$$U/U_M = (Y/\delta)^x$$

where δ is the appropriate boundary layer thickness and Y is the corresponding annular wall distance. U and U_M are the local and maximum velocities respectively, and x is the exponent which is a function of Reynolds number, Re. The simplest form of this equation is with x the same for both the inner and outer annular regions. This would seem to be an over simplification as Knudsen and Katz found that different values of x for the two zones fitted their results well.

AVERAGE VELOCITIES

A knowledge of average velocity is important, particularly in regard to the definition of friction factor. The average velocity $\bar{U}_1$ inside r_m is greater than the average velocity $\bar{U}_0$ outside r_m. In order to show the order of differences, the relation between these average velocities, the overall average velocity U and the maximum velocity U_M, have been calculated using the simple power law and the results are presented in Fig. 1.

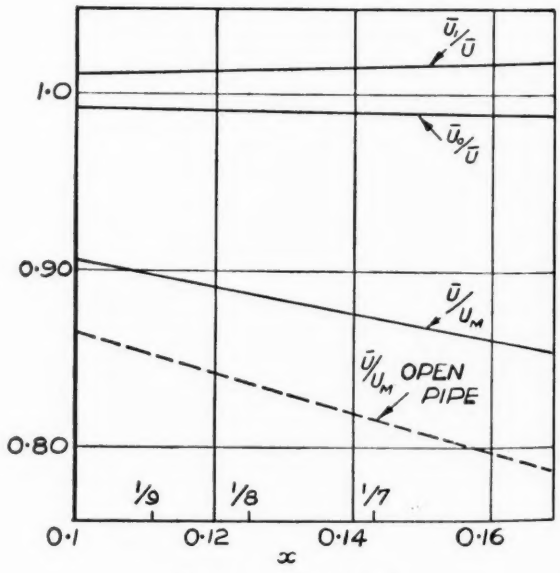

FIGURE 1. Velocity ratios.

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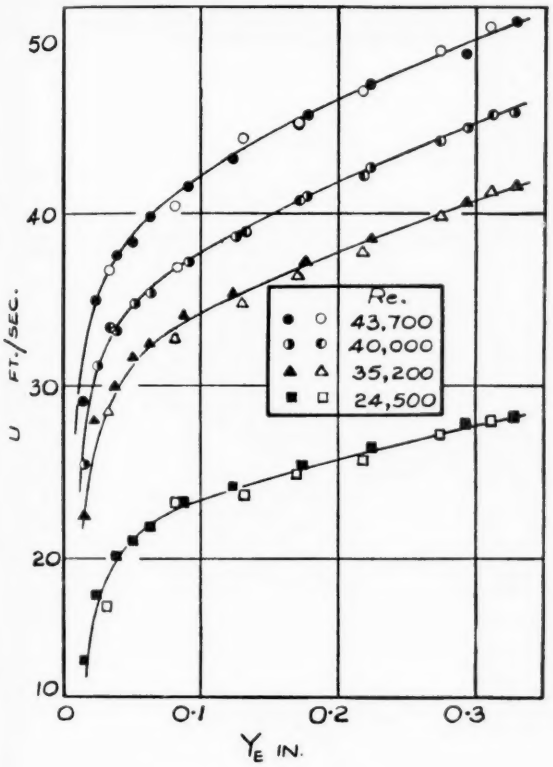

FIGURE 2. Velocity profiles.

In general,

$$\left(\frac{\bar{U}_1}{U}\right) = \frac{[r_1 + r_m(x+1)][r_0 + r_1]}{(r_m + r_1)(xr_m + r_1 + r_0)}$$

$$\frac{\bar{U}_0}{U} = \frac{[r_0 + r_m(x+1)][r_0 + r_1]}{(r_m + r_0)(xr_m + r_1 + r_0)}$$

and

$$\frac{U}{U_M} = \frac{2(xr_m + r_1 + r_0)}{(x+1)(x+2)(r_0 + r_1)}$$

The open tube result (which is independent of the physical size) is shown for comparison. (The annular velocity ratios are for a radius ratio of $2\frac{1}{4}$).

AUTHOR'S EXPERIMENTAL DATA AND ITS CORRELATION

Figure 2 shows some experimental isothermal turbulent velocity data obtained in a heat transfer study made by the author[4]. These have been plotted as equivalent open pipe profiles in the method developed by Rothfus, Monrad and Senecal, *i.e.* on a base of equivalent pipe wall distance Y_E. The data inside and outside r_m form a common profile.

It seems reasonable to expect that these equivalent profiles might be correlated by a simple power law with their parameter Y_E as the length dimension. Furthermore, the index of this law might have the same value as the accepted open pipe value.

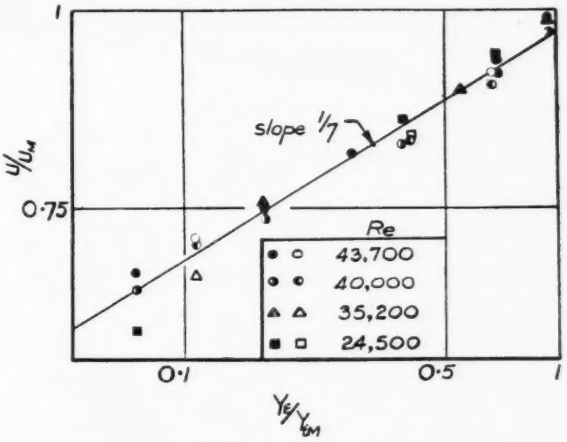

FIGURE 3. Velocity profiles.

The exponent of the suggested power law for the Reynolds number under consideration has been determined by plotting (U/U_M) against (Y_E/Y_{EM}) where Y_{EM} is the maximum value of Y_E and corresponds to r_m in the annulus.

Figure 3 shows the results. While a small variation in slope can be detected for the four tests (decreasing slope with increasing Re) a mean slope of 1/7 fits the data well. It is to be noted that this average index is the same as the average index for open pipe flow in the same Re range.

(The Reynolds number shown in the figures are the annular values. The corresponding equivalent pipe values are slightly less.)

The final equation is then

$$U/U_M = (Y_E/Y_{EM})^{1/7}$$

For an annulus of radius ratio $2\frac{1}{4}$ and core diameter $1\frac{1}{2}$ in., evaluation of the equivalent wall distances Y_E and graphical integration of this equation gives

$$\bar{U}_1/U_M = 0{\cdot}928$$

$$\bar{U}_0/U_M = 0{\cdot}903$$

and

$$\bar{U}/U_M = 0{\cdot}91$$

These results will be sufficiently accurate for other sizes which are likely to be of interest.

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On the Effect of Flow Separation on the Lift of Slender Bodies

By

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A PHENOMENON of interest in the study of high-speed aerodynamics concerns the flows generated around very slender bodies of revolution. It has been observed that these bodies, at moderate and large angles of attack, produce a kind of flow pattern that differs considerably from the ones assumed in perfect-fluid treatment according to the usual slender-body analysis.

Photographs[1] reveal that the flow above the upper surface of the body contains two symmetrically disposed spiral vortex sheets which roll up and are carried downstream. Viewed in respect to the stationary body, the shed vortices appear fixed. The vortices increase in strength as any body cross plane moves rearward, being eventually discharged to form a Kármán vortex street as viewed in the moving cross plane.

Experience has demonstrated that the phenomenon of this component flow separation causes an increase of lift.

The case where strong viscous effects require the modification of the classical body theory may be done semi-empirically, using the cross-flow concept of the Munk's slender-body theory. A solution of similar potential-flow problem for the delta wings of very small reduced aspect ratios has been proposed by Brown and Michael and others[2, 3, 4].

For a slender body of revolution which is inclined at an angle α to the stream of velocity V_0, the most appropriate two-dimensional flow in a cross plane of the body, suitable to simple calculation, is expected to be of shape similar to Fig. 1. The separation occurs at an upper surface and produces the two spiral vortex sheets which may be replaced by two concentrated vortex filaments near to the centre of the spirals.

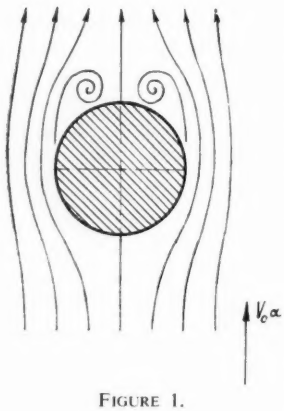

FIGURE 1.

The increase in strength of the vortex sheets in the downstream direction must be accomplished by a feeding sheet of vorticity to satisfy Kelvin's theorem. The only contribution of viscosity in this flow is to fix the separation point at the upper surface of the body.

For a similar flow it was shown[2] that the final boundary condition requires that the assumed vortex system, including feeding sheets and concentrated vortices, have zero net force acting since the fluid cannot sustain forces.

Thus, for a complete solution of the considered potential flow there are three unknowns to be determined, *i.e.* strength of the vortex and two co-ordinates of its position. For conical flow, the entire flow pattern is similar at all stations, and the strength of the concentrated vortex varies linearly from the vertex.

The complex potential function for the vertical flow shown in Fig. 2 past a circular cylinder of radius a with two symmetrically placed vortices of equal but opposite strength γ may be derived using the method of conformal mapping, and is given by

$$W(R) = \varphi + i\psi = -iV_0\alpha\left[R - (a^2/R)\right] - \frac{i\gamma}{2\pi}\log_e\frac{(R-R_v)\left[R+(a^2/R_v)\right]}{(R+R_v)\left[R-(a^2/R_v)\right]} + \text{constant},$$

where $R = y + iz$ is the complex variable in the plane YZ and $R_v = y_v + iz_v$ the position of the vortex.

At the cylinder surface, where $y = a\cos\theta$ and $z = a\sin\theta$, the velocity potential is

$$\varphi = 2V_0\alpha a\sin\theta + \frac{\gamma}{2\pi}\left\{\tan^{-1}\left[\frac{a\sin\theta - z_v}{a\cos\theta - y_v}\right] - \tan^{-1}\left[\frac{a\sin\theta - z_v}{a\cos\theta + y_v}\right] + \tan^{-1}\left[\frac{a\sin\theta - z_v\,(a^2/r_v^2)}{a\cos\theta + y_v\,(a^2/r_v^2)}\right] - \tan^{-1}\left[\frac{a\sin\theta - z_v\,(a^2/r_v^2)}{a\cos\theta - y_v\,(a^2/r_v^2)}\right]\right\} + \text{constant},$$

where $r_v^2 = y_v^2 + z_v^2$. The lifting differential pressure coefficient is, to first order,

$$\frac{\Delta p}{q} = -\frac{2}{V_0}\left(\frac{\partial\varphi}{\partial a}\frac{da}{dx} + \alpha\frac{\partial\varphi}{\partial y}\right) - \frac{1}{V_0^2}\left[\left(\frac{\partial\varphi}{\partial y}\right)^2 + \left(\frac{\partial\varphi}{\partial z}\right)^2\right].$$

Integration of the pressures acting thus yields for the body lift coefficient

$$C_L = \frac{L}{qA_0} = \frac{1}{A_0}\int_{a}^{a}\int_{0}^{l}\frac{\Delta p}{q}\,dx\,.\,dy = C_{L_0} + \Delta C_L$$

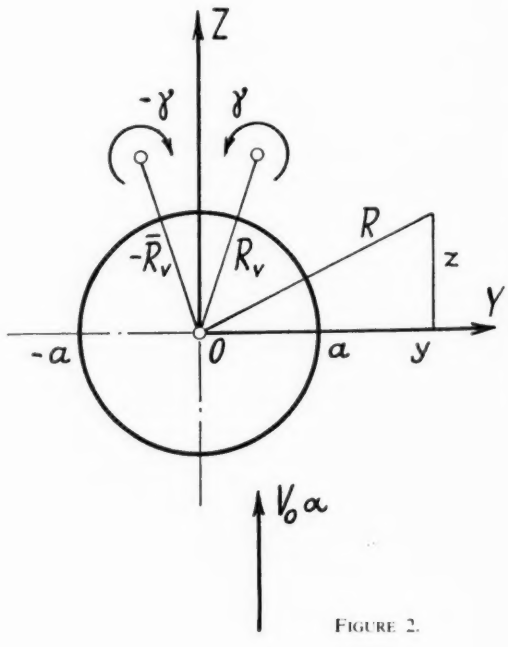

FIGURE 2.

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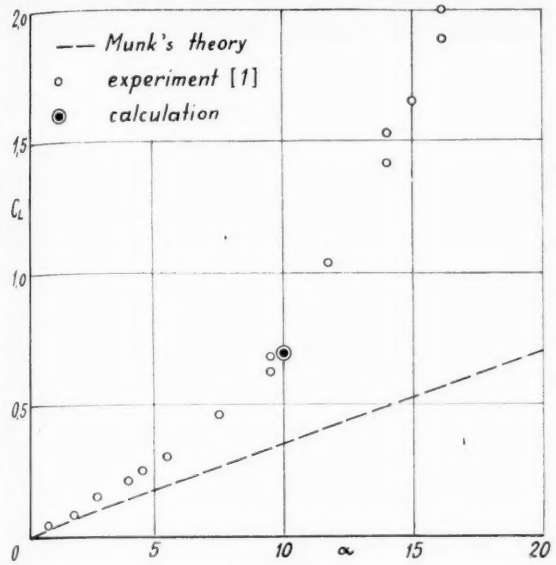

FIGURE 3.

where A_0 is base area, l body length, $C_{L_0}=2\alpha$ is the familiar result as given by the Munk slender-body theory, while ΔC_L is the additional lift coefficient due to the flow separation.

Figure 3 shows a comparison between the lift coefficient C_L calculated in this manner for a single value of the angle of attack $\alpha=10°$ and experimental values, taken from Ref. 1. The three unknowns, strength of the vortex γ and two co-ordinates y_v and z_v of its position, were estimated from the photograph. The approximate value γ was determined by considering the direction of the flow velocity at a definite point $y=a$ and $z=z_v$.

Though there is an ambiguity in the estimation of the values γ, y_v and z_v, and the calculated point does not prove anything except that there is a combination of these values that permits agreement with experiment, it is believed that the agreement between the calculated point and experiment as shown in Fig. 3 is encouraging.

This result is instructive in indicating the manner in which the effects of body flow separation, at high speeds, could be studied and predicted.

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Strut Testing

Comment by

A. H. CRAWSHAW
(Blackburn and General Aircraft Ltd.)

In the July JOURNAL, page 528, Dr. H. Fessler describes a method of testing struts using links in tension to apply the load.

A much easier and cheaper method is to use sharpened rods as struts tested between hard flat plates. As the load increases the ends continually crush so that there is no restraint and the equivalent to a pin joint is obtained.

Eccentricities can easily be obtained by bending the rods and the amount can be checked by mounting between female centres and rotating. At least three specimens of each length should be tested. A strut curve consisting of failing stress plotted against length divided by radius of gyration can then easily be obtained for use with the material, without the use of theory. If pins or ball ends are used at the ends of the struts, the frictional restraint stabilises the ends so that fixing is obtained. The equivalent pin centres may then be halved. There is therefore a large scatter in such test results.

If a load equivalent to the failing load (with length as pin centres) is applied to such a long strut in a testing machine the centre portion of the strut can be pushed from side to side by hand as if the strut were broken. If now the strut is pushed to one side the friction will hold it there and continued strain applied by the testing machine will result in a drop in load. If, however, the strut is released in the centre of the available movement further strain will result in a greatly increased failing load.

In Dr. Fessler's arrangement the pins are fixed to the ends of the strut so that if the friction between the pin and the top and bottom link are equal at one end of the strut, the frictional moments will balance and there will be no moment applied to that end of the strut; also since the pin is moving in both links in opposite directions there will be no restraint to movement of the end of the strut. If, however, as is likely, the friction in one link is greater than that in the other, the end of the strut will be rotated by this link, and since static friction is greater than kinetic friction an appreciable moment may be applied. The tests will at least be on the safe side since the moment is destabilising and not stabilising as in the usual test.

REPLY BY Dr. FESSLER

Mr. Crawshaw is not justified in assuming that the strut is fixed to the hinge pins. The drawing near *C* in Fig. 1 showed a sharpened end of the strut such as Mr. Crawshaw advocates. If rotation of the pins at *A* and *C* occurred due to differential friction in the links this could be prevented by attaching small weights to the pins and thus lowering their centre of gravity. However, the essential feature of the proposed arrangement was its stability.

Bending of Elastically Restrained Rectangular Plates Under Uniform Pressure

By

C. LAKSHMI KANTHAM

(Department of Aeronautical Engineering, Indian Institute of Science, Bangalore)

IN THE bending and vibration of plates it is found that the values of maximum deflection and natural frequencies, respectively, vary considerably from the simply-supported to clamped edge conditions. For an estimation of these characteristics in the intermediate range a generalised boundary condition may be assumed, of which the simply-supported and clamped edges become limiting cases. While Bassali[1] considers the ratio of edge moment to the cross-wise moment as a constant, Newmark[2], Lurie[3] and Klein[4] and other investigators[5, 6], in their analyses of various structures, consider that moment and slope at an end are proportional.

Here the definition of elastic restraint as given by Timoshenko[7], $\alpha=\beta M$, is followed, where α is the slope at any edge, M the corresponding edge moment per unit length while β is the elastic restraint factor. $\beta\longrightarrow 0$ and $\beta\longrightarrow\infty$ represent the two limiting cases of simply-supported and clamped edge conditions.

The problem of the bending of a rectangular plate with its edges elastically restrained against rotation is analysed here by the superposition of moments on a loaded simply-supported plate as followed first by Timoshenko[8].

NOTATION

a, b	dimensions of rectangular plate
h	thickness of plate
$k=4qa^2/\pi^3$	
q	pressure
w_1, w_2	deflections
$x, y,$	rectangular co-ordinates
D	plate constant
E	Young's modulus
E_m	) Fourier
F_m	) coefficients
M	edge moment per unit length corresponding to α
α	slope at any edge $=\beta M$
β	elastic restraint factor
$\lambda_p=\beta D/a$	

ANALYSIS

Consider a thin, elastic, rectangular plate of constant thickness as in Fig. 1, elastically restrained against rotation at its edges, the pressure acting being q.

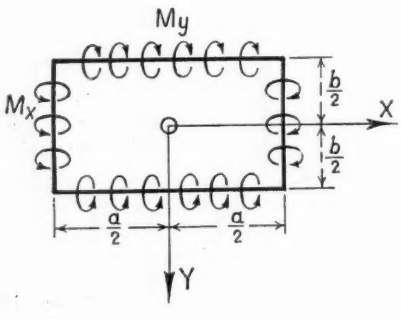

FIGURE 1.

Received October 1957.

For a thin rectangular plate loaded uniformly, with simply-supported edges with origin as in Fig. 1, the general expression for deflection using the small deflection theory may be written as

$$w=\frac{4qa^4}{\pi^5 D}\sum_{m=1,3,5,\ldots}^{\infty}\frac{(-1)^{\frac{m-1}{2}}}{m^5}\cos\left(\frac{m\pi x}{a}\right)\times\left[1-\frac{\alpha_m\tanh\alpha_m+2}{2\cosh\alpha_m}\cosh\left(\frac{m\pi y}{a}\right)+\frac{1}{2\cosh\alpha_m}\frac{m\pi y}{a}\sinh\left(\frac{m\pi y}{a}\right)\right] \quad (1)$$

where $\alpha_m=m\pi b/2a$. Equation (1) satisfies the general plate equation $\nabla^4 w=q/D$ throughout the plate.

If M_x, M_y be the moments distributed, along the edges $x=\pm a/2$, $y=\pm b/2$, and have a symmetrical distribution, then they can be expressed in a Fourier expansion as

$$(M_x)_{x=\pm a/2}=\sum_{m=1,3,5,\ldots}^{\infty}(-1)^{\frac{m-1}{2}}F_m\cos\left(\frac{m\pi y}{b}\right) \quad (2)$$

$$(M_y)_{y=\pm b/2}=\sum_{m=1,3,5,\ldots}^{\infty}(-1)^{\frac{m-1}{2}}E_m\cos\left(\frac{m\pi x}{a}\right) \quad (3)$$

The resulting slope due to the action of these moments and the load on the plate must then satisfy the relationship between the slope at any edge and the moment at the same edge.

Thus we have, from Fig. 1

$$\left.\begin{aligned}\left(\frac{dw}{dx}\right)_{x=a/2}&=-\beta(M_x)_{x=a/2}\\ \left(\frac{dw}{dx}\right)_{x=-a/2}&=\beta(M_x)_{x=-a/2}\end{aligned}\right\} \quad (i)$$

$$\left.\begin{aligned}\left(\frac{dw}{dy}\right)_{y=b/2}&=-\beta(M_y)_{y=b/2}\\ \left(\frac{dw}{dy}\right)_{y=-b/2}&=\beta(M_y)_{y=-b/2}\end{aligned}\right\} \quad (ii)$$

To get the slope at $x=a/2$, due to the load on a simply-supported plate, equation (1) is re-written as

$$w=\frac{4qb^4}{\pi^5 D}\sum_{m=1,3,5,\ldots}^{\infty}\frac{(-1)^{\frac{m-1}{2}}}{m^5}\cos\left(\frac{m\pi y}{b}\right)\times\left[1-\frac{\beta_m\tanh\beta_m+2}{2\cosh\beta_m}\cosh\left(\frac{m\pi x}{b}\right)+\frac{1}{2\cosh\beta_m}\frac{m\pi x}{b}\sinh\left(\frac{m\pi x}{b}\right)\right] \quad 1(a)$$

where $\beta_m=\dfrac{m\pi a}{2b}$

$$\text{Hence, }\left(\frac{\partial w}{\partial x}\right)_{x=a/2}=\frac{2qb^3}{\pi^4 D}\sum_{m=1,3,5,\ldots}^{\infty}\frac{(-1)^{\frac{m-1}{2}}}{m^4}\cos\left(\frac{m\pi y}{b}\right)\times\left[\frac{\beta_m}{\cosh^2\beta_m}-\tanh\beta_m\right] \quad (4)$$

and from equation (1), we get $(\partial w/\partial y)$ as

$$\left(\frac{\partial w}{\partial y}\right)_{y=b/2} = \frac{2qa^3}{\pi^4 D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m^4} \cos\left(\frac{m\pi x}{a}\right) \times \times \left[\frac{\alpha_m}{\cosh^2 \alpha_m} - \tanh \alpha_m\right]. \quad . \quad (5)$$

It can be seen from equations (4) and (5) that both the slopes are negative.

The moments M_x, M_y cause deflections w_2 and w_1 respectively which can be written in their final form (from Timoshenko[8]) as

$$w_2 = \frac{b^2}{2\pi^2 D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m^2} \frac{F_m}{\cosh \beta_m} \cos\left(\frac{m\pi y}{b}\right) \times \times \left[\frac{m\pi x}{b} \sinh\left(\frac{m\pi x}{b}\right) - \beta_m \tanh \beta_m \cosh\left(\frac{m\pi x}{b}\right)\right]. \quad (6)$$

$$w_1 = \frac{a^2}{2\pi^2 D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m^2} \frac{E_m}{\cosh \alpha_m} \cos\left(\frac{m\pi x}{a}\right) \times \times \left[\frac{m\pi y}{a} \sinh\left(\frac{m\pi y}{a}\right) - \alpha_m \tanh \alpha_m \cosh\left(\frac{m\pi y}{a}\right)\right] . \quad (7)$$

these being opposite in direction to positive w (see equation 1(a)).

$$\left(\frac{\partial w_2}{\partial x}\right)_{x=a/2} = \frac{b}{2\pi D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m} F_m \cos\left(\frac{m\pi y}{b}\right) \times \times \left[\tanh \beta_m + \frac{\beta_m}{\cosh^2 \beta_m}\right] \quad . \quad . \quad (8)$$

$$\left(\frac{\partial w_2}{\partial y}\right)_{y=b/2} = \frac{4a^2}{\pi^2 Db} \times \times \sum_{m=1,3,5,\ldots} \frac{F_m}{m^3} \sum_{i=1,3,5,\ldots} \frac{i(-1)^{\frac{i-1}{2}}}{\left(\frac{a^2}{b^2} + \frac{i^2}{m^2}\right)^2} \cos\left(\frac{i\pi x}{a}\right) \quad (9)$$

From equation (7) by differentiation:

$$\left(\frac{\partial w_1}{\partial x}\right)_{x=a/2} = \frac{4b^2}{\pi^2 Da} \times \times \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \sum_{i=1,3,5,\ldots} \frac{i(-1)^{\frac{i-1}{2}}}{\left(\frac{b^2}{a^2} + \frac{i^2}{m^2}\right)^2} \cos\left(\frac{i\pi y}{b}\right) \quad (10)$$

and

$$\left(\frac{\partial w_1}{\partial y}\right)_{y=b/2} = \frac{a}{2\pi D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m} E_m \cos\left(\frac{m\pi x}{a}\right) \times \times \left[\tanh \alpha_m + \frac{\alpha_m}{\cosh^2 \alpha_m}\right] \quad . \quad . \quad (11)$$

By superposition, using boundary condition (i) at $x = a/2$ we get from equations (4), (8) and (10),

$$\frac{2qb^3}{\pi^4 D} \sum_{m=1,3,5,\ldots} \frac{(-1)^{\frac{m-1}{2}}}{m^4} \cos\left(\frac{m\pi y}{b}\right)\left(\frac{\beta_m}{\cosh^2 \beta_m} - \tanh \beta_m\right) + + \frac{b}{2\pi D} \sum_{m=1,3,5,\ldots} \frac{F_m}{m} (-1)^{\frac{m-1}{2}} \cos\left(\frac{m\pi y}{b}\right)\left(\tanh \beta_m + + \frac{\beta_m}{\cosh^2 \beta_m}\right) + \frac{4b^2}{\pi^2 Da} \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \sum_{i=1,3,5,\ldots} \frac{i(-1)^{\frac{i-1}{2}}}{\left(\frac{b^2}{a^2} + \frac{i^2}{m^2}\right)^2} \times \times \cos\left(\frac{i\pi y}{b}\right) = -\beta \sum_{m=1,3,5,\ldots} (-1)^{\frac{m-1}{2}} F_m \cos\left(\frac{m\pi y}{b}\right) \quad (12)$$

Dividing throughout by $b/2\pi D$, and comparing coefficients of $\cos(i\pi y/b)$ equation (12) yields

$$\frac{4qb^2}{\pi^3} \frac{1}{i^4} \left\{\frac{\beta_i}{\cosh^2 \beta_i} - \tanh \beta_i\right\} + \frac{F_i}{i} \left\{\tanh \beta_i + \frac{\beta_i}{\cosh^2 \beta_i}\right\} + + \frac{8b}{\pi a} \cdot i \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \frac{1}{\left(\frac{b^2}{a^2} + \frac{i^2}{m^2}\right)^2} = -\frac{2\pi\beta D F_i}{b}$$

or

$$F_i \left\{\frac{1}{i}\left[\tanh \beta_i + \frac{\beta_i}{\cosh^2 \beta_i}\right] + 2\pi \frac{\beta D}{a} \cdot \frac{a}{b}\right\} + + \frac{8i}{\pi} \cdot \frac{b}{a} \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \frac{1}{\left(\frac{b^2}{a^2} + \frac{i^2}{m^2}\right)^2} = \frac{4qb^2}{\pi^3} \cdot \frac{1}{i^4} \times \times \left\{\tanh \beta_i - \frac{\beta_i}{\cosh^2 \beta_i}\right\}$$

Letting $\lambda_p = \dfrac{\beta D}{a}$ and $\dfrac{4qa^2}{\pi^3} = k$

we get $F_i \left\{\frac{1}{i}\left[\tanh \beta_i + \frac{\beta_i}{\cosh^2 \beta_i}\right] + 2\pi\lambda_p \frac{a}{b}\right\} + \frac{8_i}{\pi} \frac{b}{a} \times \times \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \frac{1}{\left(\frac{b^2}{a^2} + \frac{i^2}{m^2}\right)^2} = \frac{k}{i^4}\left(\frac{b^2}{a^2}\right)\left\{\tanh \beta_i - \frac{\beta_i}{\cosh^2 \beta_i}\right\} \quad . \quad . \quad (13)$

Similarly, deriving the results for $y = b/2$, from equations (5), (9) and (11), on simplification we have,

$$E_i \left\{\frac{1}{i}\left[\tanh \alpha_i + \frac{\alpha_i}{\cosh^2 \alpha_i}\right] + 2\pi\lambda_p\right\} + + \frac{8_i}{\pi} \frac{a}{b} \sum_{m=1,3,5,\ldots} \frac{F_m}{m^3} \frac{1}{\left(\frac{a^2}{b^2} + \frac{i^2}{m^2}\right)^2} = \frac{k}{i^4}\left\{\tanh \alpha_i - \frac{\alpha_i}{\cosh^2 \alpha_i}\right\} \quad . \quad . \quad (14)$$

Equations (13) and (14) reduce to one equation for a square plate, as given by

$$E_i \left\{\frac{1}{i}\left[\tanh \alpha_i + \frac{\alpha_i}{\cosh^2 \alpha_i}\right] + 2\pi\lambda_p\right\} + + \frac{8_i}{\pi} \sum_{m=1,3,5,\ldots} \frac{E_m}{m^3} \frac{1}{\left(1 + \frac{i^2}{m^2}\right)^2} = \frac{k}{i^4}\left\{\tanh \alpha_i - \frac{\alpha_i}{\cosh^2 \alpha_i}\right\} \quad . \quad . \quad (15)$$

As $\cosh^2 \alpha_i$ increases very rapidly, about four values of m are enough to obtain reasonable accuracy. Thus we have four equations in four unknown E's for the square plate (equation (15)), and for a rectangular plate eight equations in four E's and four F's (equations (13) and (14)). These values of E and F can be used to arrive at w_2 and w_1 from equations (6) and (7) at any point in the plate. The sum of deflections w_1 and w_2 at a point, superposed on the deflection at the same point in the simply-supported case gives the deflection at the point in the given case of elastic restraint.

Calculations have been made here for the deflection at

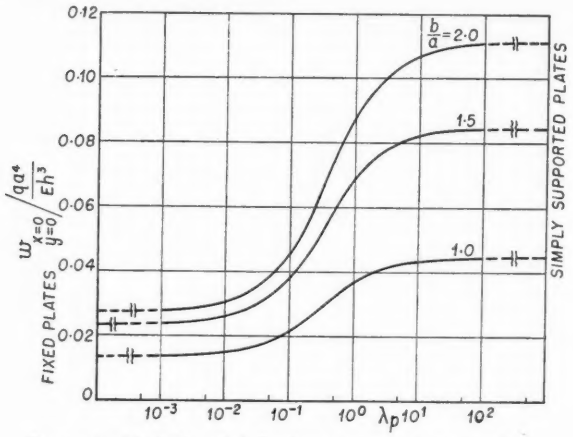

FIGURE 2. Variation of deflection at centre of rectangular plates with elastic restraint.

the centre of a plate, for different values of elastic restraint, for $b/a=1$, 1·5 and 2·0. The results are tabulated in Table I and plotted in Fig. 2. From the shape of the curves, it is seen that they approach the values for simply-supported and clamped cases asymptotically which have been taken from "Theory of Plates and Shells" by Timoshenko[8]. It can also be seen that the value of deflection for $\lambda_p=100$, is very close to that of the simply-supported case.

CONCLUSION

The curves in Fig. 2 enable us to determine the elastic restraint factor for square and rectangular plates with ratios of sides of 1·5 and 2, by measuring the deflection at the centre, when subjected to uniformly distributed loads. These results are valid only when the elastic restraint is uniform along all the edges. However, a similar procedure can be developed for the more general case of a rectangular plate with different values of elastic restraint along each of its four edges.

ACKNOWLEDGMENTS

The author's thanks are due to Mr. C. V. Joga Rao for suggesting the problem and for his guidance. The author is grateful to the Government of India for the award of a Research Scholarship during the period of investigation.

TABLE I.

VARIATION OF DEFLECTION AT THE CENTRE OF RECTANGULAR PLATES WITH ELASTIC RESTRAINT.

λ_p	$b/a=1·0$ $\frac{(w)_{x=0,y=0}}{(qa^4/Eh^3)}$	$b/a=1·5$ $\frac{(w)_{x=0,y=0}}{(qa^4/Eh^3)}$	$b/a=2·0$ $\frac{(w)_{x=0,y=0}}{(qa^4/Eh^3)}$
→ 0	0·0138	0·0240	0·0277
10^{-3}	0·0139	0·0241	0·0278
10^{-2}	0·0148	0·0257	0·0297
10^{-1}	0·0218	0·0377	0·0447
10^{0}	0·0375	0·0689	0·0874
10^{1}	0·0435	0·0823	0·1075
10^{2}	0·0442	0·0841	0·1103
→∞	0·0443	0·0843	0·1106

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Graduates' and Students' Section

Air Liners of the Future

Nearly seventy people were present for the first lecture of the autumn session, which was "The Next Generation of Civil Aircraft," by Mr. G. H. Lee, Deputy Chief Designer of Handley Page Ltd. In a fascinating talk Mr. Lee surveyed the civil aviation future, largely on the basis of considering the operating costs for different types of aircraft, and made a very strong case for the Mach 2·25 supersonic air liner.

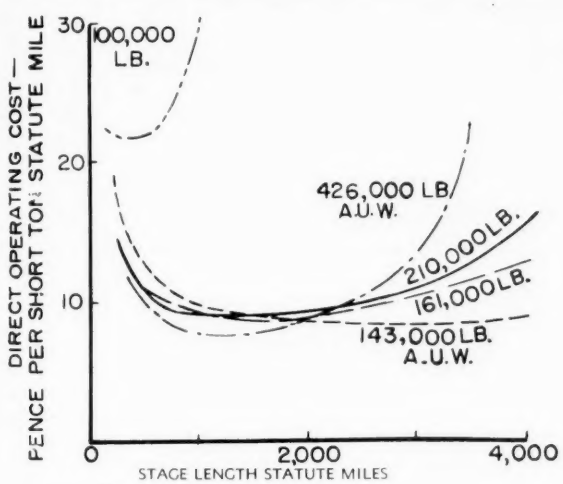
He indicated that the direct operating costs of a 1,500 m.p.h. supersonic air liner need only be about 25 per cent above those for subsonic jet transports, although costs would effectively be another 3 per cent higher because the supersonic air liner in making more journeys a day spent a greater proportion of its time in the turn-round between trips and a lower utilisation was inevitable. His calculations were based on a turbo-jet-engined slim-delta transport cruising at Mach 2·25, which was the optimum speed for range and operating costs. When carrying a 32,000 lb. payload over a stage distance of 2,500 miles the direct operating cost would be 12·5 pence per short ton statute mile.

Operating costs for this supersonic air liner were compared with those of turbo-jet and laminar-flow transports cruising at 550 m.p.h. and a turbo-prop transport cruising at 400 m.p.h. The costs for the turbo-prop and jet air liners were similar up to 2,000 miles; over longer ranges the turbo-prop costs were slightly lower. For ranges beyond 2,000 miles the laminar-flow transport had the lowest operating costs.

In discussing the design of supersonic air liners Mr. Lee showed the critical effect if weight were slightly higher than estimated or if lift/drag ratio fell short of predictions. If the basic weight went up by 5 per cent the operating cost over a 2,500 mile stage range would be increased by 120 per cent. The same increase in operating cost would also result if there were a 15 per cent reduction in lift/drag ratio. But there were two sides to this design sensitivity of supersonic air liners. There were big penalties if design aims were not achieved, but equally there could be very big gains if the design requirements were bettered and the basic weight was lower than planned or the lift/drag ratio higher than predicted.

Speaking of future developments beyond the Mach 2·25 1,500 m.p.h. air liner, Mr. Lee felt that any further increase in speed was unlikely for some time, as operating costs went up rapidly and kinetic heating became a problem.

Mr. Lee suggested that there would be great advantages if both the big jet and supersonic air liners were to make a stop at Gander when flying trans-Atlantic services. In this way operating costs between London and New York could be greatly reduced at the cost of only a slight increase in journey time.—J.R.C.



These curves compare the operating costs of a series of aircraft designed to carry a 32,000 lb. payload over a stage range of 3,000 miles (except in the case of the VTOL transport). No allowance is made in the curves for the aircraft carrying payloads greater than 32,000 lb. over the stage lengths under 3,000 miles.

Last Chance for the Dance

If you have not yet bought your tickets for the Section's annual dance there is still time to get them either from your committee member or local representative, or by post from the address given below. The dance will be held at 4 Hamilton Place, London, W.1, between 8 and 11.45 p.m. on Friday 28th November. Free wine, beer and refreshments are included in the price of the tickets, which cost only 7s. each. Postal applications, please, to: J. R. Cownie, 40 Sherwood Avenue, Marshalswick, St. Albans, Herts.

Local Representatives

Three new representatives have volunteered to represent the committee in their areas. They are E. N. Davies (Toc H Hostel, High Street, Swindon), who is with Vickers-Armstrongs (Aircraft) Ltd., at South Marston; J. Green (12 Grange Avenue, Levenshulme, Manchester 19), who is a technician with A. V. Roe and Co. Ltd., at Woodford; and M. Fraser-Mitchell (59 Cambridge Road, Kingston-on-Thames, Surrey), who is an aerodynamicist with Handley Page Ltd., at Cricklewood.

Visit to Handley Page

A visit has been arranged to the Handley Page Aircraft Co. for the morning of Saturday 20th December. It is expected that we will be able to have a close look at the Victor and Dart Herald. Both the Cricklewood and Radlett factories will be visited. The party is restricted to British born subjects. Those wishing to attend should contact the Hon. Visits Secretary, A. R. M. Pickering, "Riverside," Vicarage Walk, Bray, Berks, not later than 26th November.

Visit to Vauxhall Motors

Wednesday 21st January 1959 has been chosen for a tour of the massive and interesting production plant of Vauxhall Motors at Luton. Further details will be given next month.

Lecture Programme

The last lecture of the Autumn session will be given by Mr. E. C. Bowyer, the Director of the S.B.A.C., on Tuesday 9th December. He will talk on "The Future of The British Aircraft Industry." Mr. Bowyer is one of the most qualified people in the country to talk on such a subject and it is hoped that as many members as possible will attend. As usual free coffee will be served from 7 p.m. onwards.

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Reviews

HIGH ALTITUDE AND SATELLITE ROCKETS. *Royal Aeronautical Society and British Interplanetary Society, London, 1958. 136 pp. Illustrated. 32s. 6d.*

This volume is the proceedings of the Symposium held at the College of Aeronautics, Cranfield, from 18th to 20th July 1957, under the joint auspices of the College, the Royal Aeronautical Society, and the British Interplanetary Society.

In his Foreword, A. D. Baxter explains that the original proposal to hold the meeting emanated from members of the College staff who were also members of both Societies, and that each of these bodies welcomed the idea when it was put to them. The Symposium was attended by some 200 delegates from nine countries; this reviewer was one of them, and can testify to the success of the occasion. The attractively-produced proceedings have done it justice, and form one of the best available single sources of reference on the varied collection of subjects relevant to the title of the book.

The twelve papers included, by British and American authors, are: "The Scientific Applications of Rockets and Satellites," by H. S. W. Massey; "The Satellite Launching Vehicle," by M. W. Rosen; "British Upper Atmosphere Sounding Rocket," by W. H. Stephens; "Some Propulsion Problems of High Altitude Rockets," by A. D. Baxter; "Design Problems of Large Rockets," by K. J. Bossart; "Recovery After Re-entry, by the Use of Aerodynamic Lift," by W. F. Hilton; "Dynamics of a Dissociating Gas: Non-Equilibrium Theory," by N. C. Freeman; "High Temperature Materials in Relation to the Satellite Re-entry Problem," by P. Murray; "Some Problems of Instrumentation, Telemetry and Guidance," by A. W. Lines; "Problems of Respiratory Metabolism in Sealed Cabins," by H. G. Clamann; "Psycho-Physiological Hazards of Satellite Flight," by J. P. Henry; "Future Developments in Rocket Propulsion Beyond the Atmosphere," by L. R. Shepherd.

These titles speak for themselves, as regards the comprehensive coverage of the many aspects of astronautics, while most of the authors need no introduction to students of this science. They include the designer of the Atlas I.C.B.M., the Technical Director of the Vanguard satellite project, the Chairman of the Royal Society Committee co-ordinating all British high-altitude physical research, the present Chairman of the British Interplanetary Society (also well-known as a nuclear physicist), as well as a number of this country's leading aeronautical scientists.

Not the least of this volume's virtues is its inclusion of the well-reported discussions following the lectures; these add greatly to the interest and value of the work. One might follow the Prime Minister's recent example of "tooting," and say that this sort of thing is done very well by this country. Others might learn from us in this respect, as regards the ordering of international scientific meetings.

Also included in the volume is a statement on the "U.S.S.R. Rocket and Earth Satellite Programme for the I.G.Y.," made at the Symposium by Prof. Boris M. Petrov, of the Academy of Sciences. Among other things, he said: "In the Soviet Union, during the I.G.Y. the first launching of a man-made satellite for scientific purposes will be made." These were indeed prophetic words!

The Cranfield meeting was of course held just eleven weeks before Sputnik I projected us all into the Space Age. One might sympathise with Milton Rosen over the subsequent tribulations of the Vanguard, though his paper remains an excellent discussion of general satellite problems, and in any case he can console himself with the fact that Vanguard's puny "grapefruit" will still be orbiting many years after all the Sputniks (so far) have burned up in fiery plunges back into the atmosphere. I remember discussing the Russian competition with him at Cranfield, when he said: "We're doing all we can. If they beat us to it, it's just too bad, but if they do—the best of luck to them."

All of which seems relevant to a contribution I am reported as making to Shepherd's concluding paper:

". . . friendly rivalry in space-flight may, and probably will, develop as one of the important features of the increasing competition for international prestige. There could be much worse ways in which this competition could progress, from anyone's viewpoint."

More than ever, it seems likely that this was a true prediction. More than ever, I hope that it was.—A. V. CLEAVER.

BASIC AERONAUTICAL SCIENCE AND PRINCIPLES OF FLIGHT. *Robert D. Blacker. The Technical Press, London, 1958. 242 pp. Illustrated. 50s.*

The author of a text-book of normal length may choose to write in detail about one particular aspect of his subject and he will be expected to be a master of this special topic. Those who are not specialists sometimes feel tempted to write a text-book covering a much wider field in which little detail can be included and ignorance can be smothered in generalities. Most teachers will agree that imparting specialist knowledge to mature students is their easiest assignment: general principles to the immature demands a teacher of the highest calibre.

Robert D. Blacker is an American pilot and aeronautics instructor. His book assumes no previous knowledge of science and, with the aid of over a thousand diagrams and photographs, supplies "an extensive fund of general information" about aircraft. Aeroplanes of all kinds are described together with their power systems, instruments and accessories, meteorology and navigation, principles of flight, history of aviation, careers in aviation—all these are explained together with some basic mechanics.

The author seems to be talking to the immature—but to which category? Children, I find, appreciate the simple diagrams but are unlikely to have 50s. The semi-literates who read the American comics are catered for (one drawing in the chapter on structures shows a boy jumping up and down on the wing of a light aeroplane. The caption is "They sure do make 'em strong")—but do these readers buy text-books? The publishers have added a ridiculous dust cover which shows two conventional jet fighters circling the moon some 200,000 miles above California. This is hard on the author who managed to confine himself to aircraft which fly in the earth's atmosphere.

There are several errors in the text. The author does not appear to understand cyclic pitch control on helicopter rotors and attributes the need for increased power during the climb of a normal aeroplane to increased drag arising from the increased angle of attack! A novel feature is

the inclusion at the end of each chapter of a "self-examination." Questions are posed to check the reader's mastery of the subject matter and many of these questions typify all that is worst in examinations. Semi-literates will be pleased to find that they can answer most by writing *T* or *F* (true or false) or by ticking (*a*), (*b*), (*c*) or (*d*). There are questions to which there is no answer—"The angle between the wings and the horizontal is called (*a*) dihedral; (*b*) delta; (*c*) cantilever; (*d*) semi-cantilever" and, "The potential usefulness of the airplane was first recognised in Europe. *T* or *F*?" Other questions are obviously designed for morons—"Charts are arranged so that north always lies at the (*a*) left; (*b*) right; (*c*) bottom; (*d*) top" but where does the polar navigator place his tick? Some are mystifying. "Weight increase of an aircraft while in flight is dangerous. *T* or *F*?" The answer at the end of the book is *T* but refuelling in flight seems safe enough.

If you buy this book you will be wasting your money. *T* or *F*?—A. H. YATES.

AN INTRODUCTION TO THE DYNAMICS OF AIRPLANES. *H. Norman Abramson. Ronald Press, New York. 1958. 225 pp. Illustrated. 4.50 dollars.*

This book, in accordance with its title, provides a general introduction to the dynamics of aircraft at a fairly elementary level within the bounds of its 225 pages. The author states in his Preface: "The purpose of this book is to present the basic principles and ideas concerning airplane dynamics problems which should be included in the "tool kit" of today's aeronautical engineering graduate. The material presented here purposely avoids concentration on the details of any particular analysis, but rather tries to present the general picture of airplane dynamics problems. This volume is not intended as a reference text for dynamics specialists; instead, it is written on a level for senior college students in aeronautical engineering who have had only the usual second- or third-year course in elementary dynamics and an introductory course in differential equations." This gives a correct and adequate indication of the level of treatment of topics and the scope of the book.

The first two chapters are concerned with the vibrations of systems having one or several degrees of freedom. These are followed by a chapter of 24 pages on "Elements of Matrix Algebra with Applications." Chapter 4 treats the topics of stability and self-excited vibrations in a general and elementary way and this is followed by chapters on wing flutter and on aeroelasticity in general. Chapter 7 deals with problems of impulsive loading—landing impact, gust response and buffeting. There is a brief account of the stability of flight in Chapter 8, while the final chapter is devoted to miscellaneous topics; there are two mathematical appendices.

Perhaps inevitably in a short book which attempts to cover a very wide field the treatment sometimes tends to be superficial. However, the book should provide a helpful introduction to its subject. Lists of references are given at the end of each chapter; these are almost exclusively to American sources.—W. J. DUNCAN.

FLYING MATILDA. *Norman Ellison. Angus and Robertson. London. 340 pp. Illustrated. 25s.*

This is really two books: the first 190 pages a kind of scrapbook of Australian air history and the remaining 150 pages a biography of the late Sir Charles Kingsford Smith. The second book is by far the more important and is well worth reading by students of air history. Why the two books should have been published together as one volume is not clear and the reader is left with regrets that the biography—properly completed—was not published on its own.

There have, of course, been a number of other biographies of Kingsford Smith, including at least one so-called autobiography, as well as books about several of his flights but this latest study contains a lot of information about that outstanding pilot which has not previously appeared in print. Indeed, Norman Ellison, who knew Kingsford Smith and his family, gives a vivid living picture of the man which rings true. He provides a new viewpoint on a number of controversial aspects of his subject's aviation career and is unusually frank—even for an Australian!—about the facts behind the various spates of criticism to which Kingsford Smith was subjected by his countrymen during certain phases of his life.

Because Mr. Ellison had access to all Kingsford Smith's letters to his family—which were fortunately preserved—and had contacts with his close relations, he has been able to give a far more complete picture of the man's early life and of that part of his flying career before he became well-known than has any previous writer. This section of the biography is complete and is well done. The remainder is little more than a summary of the main part of Kingsford Smith's career which has already been much written about. It is a pity that Mr. Ellison did not face up to the job of making his book into a complete account. He had the material and there is certainly a need for a proper appraisal of the life of one of the World's greatest airmen.

The first pages—the historical scrapbook part—contain an untidily arranged and rather irritating series of anecdotes about unrelated events and personalities of Australian air history. There are humorous stories—some in rather questionable taste—biographical snippets about characters important and unimportant, and much emphasis on the rowdy, looting, drunken and irresponsible individuals whom the author obviously considers made an important contribution to the "atmosphere" of the pioneering days of aviation in Australia. The "atmosphere" is certainly there and this part of the book is easy, if unproductive, reading but one doubts very much whether the picture is truly painted. There was more than this to the early days of the R.A.A.F. and the Australian air transport industry.

The historian with sufficient patience will pick up a few worthwhile scraps from even this higgledy-piggledy mixture but these are of limited value because of an almost complete lack of dates—there is, however, quite a good index. There are a number of inaccuracies (the Supermarine Seagull was not a "twin-pontoon" seaplane with a rotary engine, nor did the Avro Avian exist in 1919 nor have a rotary) but the errors are fewer than might be expected in view of the casual style and it is clear that Mr. Ellison knows his aeroplanes.

It is a pity he did not concentrate on his biography of Kingsford Smith. With little more effort that part of his book could have been made into something really worthwhile.—PETER W. BROOKS.

THE ZERO FIGHTER. *Mesatake Okumiya and Jiro Horikoshi with Martin Caidin. Cassell, London. 288 pp. Illustrated. 30s.*

This unique record of the development of the Mitsubishi A6M Zero carrier fighter deserves to be read by all those members of design teams and official bodies who are responsible for the specification and conception of new aircraft. Jiro Horikoshi was Chief Designer of the team which produced the Zero, and the book is largely his own account of the design and development of the aircraft,

which first flew in April 1939. Its value to us in 1958 lies not so much in the detailed technical history of the Zero, fascinating though this is, as in the exposition of the design philosophy and the lessons to be learnt of the benefits and, later, of the penalties which result from over-emphasis on one particular aspect of operation performance.

The Zero fighter specialised in combat manoeuvrability. From the first outline specification in 1937 the Japanese Navy insisted that the aircraft must have unexcelled dog-fighting ability. To this end the designers built in many factors (chiefly low wing loading and span loading and a low design diving speed) and sacrificed other features (armour protection, self-sealing fuel tanks, and so on) such that in its combat baptism in China during 1940 and in the early phases of the Pacific War, the Zero outmanoeuvred and outfought the existing fighter opposition and was supremely successful. In later years, however, these same features were responsible for the combat inferiority of the Zero when opposed by American fighters of more balanced design with superior handling at high indicated air speed, and heavier fire-power.

By the time the Japanese Navy had officially recognised these shortcomings the aircraft and engine production situation in Japan had deteriorated beyond hope of recovery. Promised increases of engine power, which were to revitalise the Zero, did not materialise and the chosen successor to the Zero—the A7M Sam, initiated in 1942 and also designed by the Mitsubishi team under Horikoshi—was so beset by difficulties that only a few prototypes and a handful of production aircraft were completed. At the end of the war the B29 bombing campaign had been so successful that the U.S. Technical Mission could not find enough components to assemble one airworthy Sam.

Conditioned as most of us are to the popular view that the Japanese engineer excels more in copying than in creating, it is rather a shock to learn how advanced their aircraft technology became. For example, in 1940, after the loss of the second prototype Zero, the Naval Aircraft Establishment flew simulated combat sorties in Zero aircraft fitted with *g*-recorders to obtain a statistical loading spectrum. This data was then used to estimate the wing spar fatigue life and to form the basis for a programme of repeated-loading tests on Zero main spars. Further, it was the failure in flight of an early production Zero which led to the development of reliable dynamically similar wing models for wind tunnel flutter tests as early as 1941. But perhaps the most astonishing technological ingenuity, by Western standards, was the use in the Zero, and later fighters, of deliberate flexibility in the elevator circuit in order to increase the stick movement per *g* at high indicated air speeds. Horikoshi claims that this made a major contribution to the handling qualities of his designs. This reduced rigidity concept was patented by Horikoshi in 1940 and as a result of the success of the idea in the Zero he even recommended the withdrawal, from the Japanese equivalent of A.P.970, of the requirement calling for not more than 12·5 per cent stretch of the control circuit at the limit loading. The book does not record whether flutter tests on these elastic longitudinal controls were ever made, nor does it comment on whether such tests were thought desirable.

It is, one feels, a pity that more photographs directly relevant to the aircraft dealt with could not have been included. More serious is the omission of three-view drawings of the Zero and of Horikoshi's later fighters: this should be a first-priority modification if the book is reprinted. There are a few misprints of the "for-pilot-read-pitot" variety but the facts given about non-Japanese aircraft appear to be honest and accurate. The "special section devoted to the production and use of Japanese guided missiles during the Second World War" promised by the dust cover blurb was not in the reviewer's copy.

Immediately after reading this book the question comes to mind, "why can we not have a similar treatment of some of our better-known British fighters?" One hopes that the publication of *The Zero Fighter* may result in such a fortunate consequence.—J. W. FOZARD.

PLANE CRASH. *Clayton and K. S. Knight. Elek Books, London, 1958. 204 pp. 18s.*

The gruesome dust cover, sensational title and obvious American origin of this book suggest, at first sight, that it is just another superficial and spectacular exploitation in print of the public's morbid interest in the dramatic aspects of air accidents. Indeed, the casual bookshop browser who glances through this book alongside Oliver Stewart's recent *Danger in the Air* will probably decide—as did this reviewer—that the British book is easily the best of the two and will spend his money accordingly. However, if he does, he will be quite mistaken.

Anybody who reads *Plane Crash* from cover to cover will find that, far from being sensational in its approach, this book is an admirably prepared digest of the investigation reports on a carefully-selected cross-section of, mostly American, airline accidents which have taken place during the past twenty years. The whole book reflects that—compared with Europe—much more mature attitude of mind which the American public has towards air transport.

The authors have taken great pains to reproduce in their writing the completely unbiased and objective approach to the accidents considered which is such a vital ingredient of all satisfactory accident investigation. The result is reassuring to the airline passenger and brings out convincingly the vital part that lessons learnt from accidents play in steadily improving the safety of air transport.

The reader of *Danger in the Air* might be forgiven if he is left with a number of unhappy doubts about the causes of accidents and the effectiveness of the remedial action taken to avoid their repetition. *Plane Crash* leaves no such uncertainties. If anything, the explanation of causes and effects is too glib and the corrective action described is sometimes, to the informed reader, too straightforward. However, this is a good fault in a book for the general reader. The whole subject of air accidents and air safety is so complicated and hedged-about by modifying factors that the layman must be given an over-simplified picture if his understanding and confidence is to be won and retained.

Altogether, this is an excellent book. Although not as comprehensive as Major Stewart's, it deals with a representative variety of transport aircraft accidents and does so with more respect for the careful researches and findings of the expert investigators whose work is described. One of the few obvious errors in *Plane Crash* appears in what is perhaps its least satisfactory chapter—that which summarises the story of the Comet disasters—B.E.A. is described incidentally as being a subsidiary of B.O.A.C.!—PETER W. BROOKS.

NOTES ON ANALOG-DIGITAL CONVERSION TECHNIQUES. *Alfred K. Susskind (Editor). Chapman and Hall. London, 1958. 421 pp. Illustrated. 80s.*

This book is a useful result of two Special Summer Programs held at Massachusetts Institute of Technology in 1956 and 1957. It collects together material which is scattered in the literature and not readily accessible.

The book discusses the techniques that are used in

converting data, and exhibits both the theoretical and practical difficulties that are encountered. The problems of buffering, sampling and quantising are discussed in some detail.

One chapter is devoted to the selection and properties of particular digital codes and the advantages of the more sophisticated ones are pointed out. A number of conversion schemes are given, and both voltage and positional encoders are dealt with. A valuable feature is the list of references which is given at the end of each chapter.

This book is recommended to those interested in the subject.—D. J. WHEELER.

Additions to the Library

Aeronautical Statutes and Related Material. U.S. Civil Aeronautics Board. U.S.G.P.O. (H.M.S.O.). Revised December 1957. 394 pp. 9s. The Civil Aeronautics Act of 1938 as amended and other provisions relating to Civil Aeronautics (in the U.S.A.).

Air Forces of the World, The. W. Green and J. Fricker. Macdonald, London. 1958. 334 pp. Illustrated. 60s. *To be reviewed.*

Air Intake Problems in Supersonic Propulsion. Agardograph 27. J. Fabri (*Editor*). Pergamon Press, London. 1958. 82 pp. Diagrams. 30s. Papers presented at the 11th AGARD Combustion and Propulsion Panel Meeting in Paris in December 1956. The four lectures give the views on the intake-engine matching problem of P. Carrière and L. Viaud, of O.N.E.R.A., D. D. Wyatt, of N.A.C.A. Lewis, and Antonio Ferri, of the Polytechnic Institute of Brooklyn, with an Introduction by J. Fabri, of O.N.E.R.A.

Aircraft and Missile Propulsion. Vol. I. Thermodynamics of fluid flow and application to propulsion engines. M. I. Zucrow. John Wiley, New York. 1958. 538. 92s. *To be reviewed.*

Aircraft Annual 1959. J. W. R. Taylor (*Editor*). Ian Allan. 1958. 96 pp. Illustrated. 10s. 6d. Although the "blurb" implies that this annual is aimed at an adult audience it will have its greatest sales among teenage enthusiasts. The contributors are well-known and most of the recent developments are covered.

British Weather in Maps. J. A. Taylor and R. A. Yates. Macmillan, London. 1958. 256 pp. Illustrated. 21s. *To be reviewed.*

Capacity of Airports, The. T. Rallis. Extract from Ingenioren No. 3. 1958. 13 pp.

Cassell's Italian-English English-Italian Dictionary. P. Rebora (*Compiler*) with the assistance of F. M. Guercio and A. L. Hayward. Cassell. 1958. 1079 pp. 30s. *Not available for loan.*

Conference on Extremely High Temperatures. H. Fischer and L. C. Mansur (*Editors*). John Wiley, New York. Chapman and Hall, London. 1958. 257 pp. Illustrated. 78s. Based on the Conference on Extremely High Temperatures held in March 1958 in Boston, this is a summary of the underlying basis for commercial or usable thermonuclear reactions. Emphasis is on high temperatures as they relate to the propulsion fields, with sub-emphasis on the physics of the topics covered. The 22 papers are in four groups: The production of extremely high temperatures, methods of temperature measurement—optical radiation, plasma analysis, and applications. A paper on the behaviour of materials subjected to ultra-high temperature is included.

Control System Components. J. E. Gibson and F. B. Tuteur. McGraw-Hill, London. 1958. 493 pp. 93s. *To be reviewed.*

Electricity in Aircraft. F. G. Spreadbury. Constable, London. 1958. 342 pp. Illustrated. 40s. *To be reviewed.*

English-Russian, Russian-English Electronics Dictionary. U.S. Department of the Army. McGraw-Hill, London. 1958. 943 pp. 62s.

Festschrift Jakob Ackeret zum 60 Geburtstag 17, Marz 1958. J. Ackeret *et al* (*Editors*). Special number. Z.a.M.P. Birkhauser Verlag. 777 pp. Diagrams. 24 Swiss Francs. *To be reviewed.*

Flight into Danger. John Castle and Arthur Hailey. Souvenir, London. 1958. 162 pp. 11s. 6d. An airliner is crossing Canada at night when both pilots and some of the passengers become ill due to food poisoning. A passenger, a salesman now but ten years ago a fighter pilot, is the only person with any knowledge of flying. The building up of this drama is very tense indeed and the technicalities involved in flying a complicated four-engined aircraft are well described. Almost the only false note is the unsatisfactory explanation of the loss of radio contact at an alarming moment, but this is an excellent evening's entertainment.

Gas Turbines for Aircraft. A. W. Judge. Chapman and Hall. 1958. 439 pp. 60s. *To be reviewed.*

Gliding: A Handbook on Soaring Flight. D. Piggott. A. and C. Black, London. 1958. 261 pp. Illustrated. 25s. *To be reviewed.*

Glossaire des Termes Techniques en Usage dans le Domaine des Projectiles Guides. (Duplicated.) Union de l'Europe Occidentale, Paris. 114 pp. An English-French dictionary each definition of which is numbered. A French-English index refers to the numbered equivalent. Definitions were supplied by the Ministry of Supply and the R.A.F. Technical College and the translations came from La Direction des Etudes et Fabrications d'Armement. *Not available for loan.*

Heat Transfer and Fluid Mechanics Institute. Preprints of Papers. Stanford University Press (Oxford University Press). 1958. 264 pp. Diagrams. 60s. A paper-backed volume of photo-reproductions of the preprints of papers read at the meeting at the University of California, Berkeley, in June 1958. Twenty-one papers dealing with fluid dynamics, dynamics of reactive fluids, heat transfer, magnetohydrodynamics and hypersonics by American authors, including H. W. Emmons, E. R. G. Eckert, David Margolis, P. H. Rose, S. M. Bogdonoff, P. A. Libby and Rolf K. Landshoff.

Introduction to Fluid Dynamics. F. J. Bayley. Allen and Unwin. 1958. 215 pp. Diagrams. 28s. *To be reviewed.*

Juan de la Cierva y su Contribucion al Desarrollo de las Aeronaves de Alas Giratorias. P. D. Pedraza. Asociacion de Ingenieros Aeronauticos. Madrid. 1958. 23 pp. Bibl. 34 pp. The text, in Spanish, of the Cierva lecture delivered at the Madrid Conference. It describes Cierva's influence on the development of rotating wing aircraft, is well illustrated and concludes with a table of Cierva types, a list of the honours and awards given to Cierva and a 26 item bibliography.

Nuclear Rocket Propulsion. R. W. Bussard and R. D. DeLauer. McGraw-Hill, London. 1958. 370 pp. 77s. 6d. *To be reviewed.*

Plane Crash. Clayton and K. S. Knight. Elek Books, London. 1958. 204 pp. Illustrated. 18s.

Polar Atmosphere Symposium. Part I. Meteorology Section. Agardograph 29. R. C. Sutcliffe (*Editor*). Pergamon, London. 1958. 341 pp. Illustrated. 70s. *To be reviewed.*

S.A.E. Transactions 1958 Volume 66. Price 3 dollars to members, 8 dollars to public and college libraries, 11 dollars to non-members. *Not available for loan.*

von Richthofen and the Flying Circus. H. J. Nowarra and K. S. Brown (*Compilers*). Harleyford Publications. 1958. 207 pp. Illustrated. 45s. *To be reviewed.*

Zero Fighter, The. M. Okumiya *et al.* Cassell, London. 1958. 280 pp. 30s.

Reports

AERODYNAMICS

Boundary Layer

Effects of fixing transition on the transonic aerodynamic characteristics of a wing-body configuration at Reynolds numbers from 2·4 to 12 million. L. W. Hunton. N.A.C.A. T.N. 4279. July 1958.
A wing-body combination having a plane tapered wing of aspect ratio 3 and 3 per cent thick biconvex sections was tested. Lift, drag, and pitching-moment results are shown for Mach numbers from 0·7 to 1·3 and Reynolds numbers from 2·4 to 12 million.—(1.1.2.3).

Boundary layer stability diagrams for electrically conducting fluids in the presence of a magnetic field. V. J. Rossow, N.A.C.A. T.N. 4282. August 1958.
Neutral stability curves pertaining to a two-dimensional infinitesimal sinusoidal disturbance are presented for the laminar flow of an incompressible, electrically conducting fluid over a semi-infinite flat plate in the presence of either a coplanar or transverse magnetic field.—(1.1.1.1 × 1.4).

The use of boundary layer control to establish free streamline flows, being an introduction to the free streamline flap. D. G. Hurley and N. Ruglen. A.R.L. Report A. 109. April 1958.
The wing flap combination is represented by two flat plates hinged together at their trailing edges and solutions of the potential flow when the leading edges of the two plates are joined by a free streamline are described. Two dimensional pressure plotting experiments were made in which the length of the upper plate was 0·6 times the length of the lower plate and the leading edge of the former was rounded and fitted with a narrow blowing slot.—(1.1.6.1 × 1.3.4).

Compressible Flow—*see also* Loads
Thermo-Aerodynamics
Mathematics

A shock-expansion theory applicable to wings with attached shock waves. L. M. Sheppard and K. D. Thomson. C.P. 392. 1958.—(1.2.3.2 × 1.10.1.2).

Internal characteristics and performance of an aerodynamically controlled, variable-discharge convergent nozzle. J. G. McArdle. N.A.C.A. T.N. 4312. July 1958.
Analytical expressions relating the performance with significant operating and design variables were developed, and experimental coefficients were evaluated. Some configurations were operated as jet deflectors.—(1.2 × 1.5.1).

A review of the thermodynamic, transport, and chemical reaction rate properties of high-temperature air. C. F. Hansen and S. P. Heims. N.A.C.A. T.N. 4359. July 1958.
Thermodynamic and transport properties of high-temperature air, and the reaction rates for the important chemical processes which occur in air, are reviewed. Semi-empirical, analytic expressions are presented for thermodynamic and transport properties of air. Examples are given illustrating the use of these properties to evaluate (*i*) equilibrium conditions following shock waves, (*ii*) stagnation region heat flux to a blunt, high-speed body, and (*iii*) some chemical relaxation lengths in stagnation region flow.—(1.2.3 × 1.9.1).

Hypersonic flow about a thin body of revolution. R. Timman. AGARD Report 141. July 1957.
The boundary layer equations are derived for a thin body of revolution in hypersonic flow, taking into account the curvature of the body. A "similar" solution is found and the application of a Pohlhausen method with a suitable simple velocity profile gives the effect of radius of curvature in general terms.—(1.2.3.1).

Control Surfaces—*see also* Boundary Layer
Aeroelasticity

Wind-tunnel investigation at low speeds of flight characteristics of a sweptback-wing jet-transport airplane model equipped with an external-flow jet-augmented slotted flap. J. L. Johnson. N.A.C.A. T.N. 4255. July 1958.
The investigation was made over a lift-coefficient range up to about 12·5 for a range of angles of attack from −12° to about 13°. For lift coefficients higher than about 6, a downwardly directed nose jet was used to supplement the trimming power of the horizontal tail.—(1.3.4).

Fluid Dynamics—*see also* Boundary Layer
Mathematics

Statistical study of turbulence-spectral functions and correlation coefficients. F. N. Frenkiel. N.A.C.A. T.M. 1436. July 1958.
An extensive discussion is given of various possible correlation functions for homogeneous and isotropic turbulence. The logical consequence of each of several choices of such correlation functions is examined in detail.—(1.4.2 × 31.3.1 × 33.1.2).

Internal Flow—*see also* Compressible Flow

Analytical relation for wake momentum thickness and diffusion ratio for low-speed compressor cascade blades. S. Lieblein. N.A.C.A. T.N. 4318. August 1958.
Derivation of the simple equation for blade-wake momentum thickness as a function of suction-surface diffusion ratio is presented. The equation is based on boundary layer theory in conjunction with simplifying approximations and empirical constants.—(1.5.4.1 × 1.5.2.1).

Loads—*see also* Stability and Control
Aeroelasticity

Pressure distributions at transonic speeds for slender bodies having various axial locations of maximum diameter. J. B. McDevitt and R. A. Taylor. N.A.C.A. T.N. 4280. July 1958.
The measured static-pressure distributions at the model surface and in the surrounding flow field are presented for a related series of five bodies of revolution having various axial locations of maximum cross-sectional area. The bodies were tested at zero angle of attack through a Mach number range from 0·80 to 1·20.—(1.6.1 × 1.2.2).

An estimate of the fluctuating surface pressures encountered in the re-entry of a ballistic missile. E. E. Callaghan. N.A.C.A. T.N. 4315. July 1958.
An analysis of the sound pressure levels encountered during the re-entry of a blunt-nosed vehicle shows the probability of the existence of levels of 150 db. or more. The exposure time to high levels is of the order of 25 secs. The results are in terms of dimensionless parameters, which cover a wide range of conditions in regard to body size and weight and re-entrance angle and velocity.—(1.6.3 × 25.2 × 5.6).

Stability and Control

The longitudinal response of an aircraft with auto-pilot, including an incidence term in the height control equation. M. R. Watts and D. E. Fry. C.P. 396. 1958.
The results of a theoretical investigation into the dynamic stability of an aircraft under automatic height control are given.—(1.8.2.2).

Aerodynamic research on fuselages with rectangular cross section. K. Maruhn. N.A.C.A. T.M. 1414. July 1958.
The two-dimensional flow characteristics around square and rectangular cross sections with rounded edges as calculated by conformal mapping techniques are presented and compared with corresponding results from elliptical and rectangular cross sections. A few examples of the fuselage induced rolling moment due to sideslip are presented.—(1.8 × 1.6.1).

Low-speed experimental determination of the effects of leading-edge radius and profile thickness on static and oscillatory lateral stability derivatives for a delta wing with 60° of leading-edge sweep. H. S. Fletcher. N.A.C.A. T.N. 4341. July 1958.
Six delta-wing models with 60° of leading-edge sweep were oscillated about their vertical axes to determine the effects of systematic variation of leading-edge radius and profile thickness on the in-phase and out-of-phase combination lateral stability derivatives resulting from the motion.—(1.8.1.2 × 1.10.2.2).

Determination of longitudinal stability and control characteristics from free-flight model tests with results at transonic speeds for three airplane configurations. C. L. Gillis and J. L. Mitchell. N.A.C.A. Report 1337. 1957.

Techniques have been developed for determining aerodynamic performance and the longitudinal stability and control parameters from an analysis of transient oscillations obtained in free-flight tests of rocket-propelled models. Details of the techniques have been indicated and the feasibility of the methods for determining both linear and nonlinear aerodynamic characteristics has been demonstrated by data measured in the transonic speed range on several aeroplane configurations.—(1.8.2.2 × 1.12.2 × 1.6.1).

THERMO-AERODYNAMICS—*see also* COMPRESSIBLE FLOW

Heat-transfer and pressure measurements on flat-faced cylinders at a Mach number of 2. *W. E. Stoney and J. T. Markley. N.A.C.A. T.N.* 4300. *July* 1958.
Flat-faced cylinders of 12 in. diameter and 4 in. diameter were tested at a Mach number of 2 and sea-level conditions in a pre-flight jet.—(1.9.1 × 1.2.3).

A comparison of two methods for calculating transient temperatures for thick walls. J. J Buglia and H. Brinkworth. N.A.C.A. T.N. 4343. *August* 1958.—(1.9.1).

WINGS AND AEROFOILS—*see also* COMPRESSIBLE FLOW STABILITY AND CONTROL

High Reynolds number tests on a 70° *L.E. sweepback delta wing and body* (*H.P.* 100) *in the compressed air tunnel. R. W. F. Gould and C. F. Cowdrey. C. P. No.* 387. 1958.
Values of lift, drag and pitching moment coefficients are given for a model of the H.P. 100 delta wing with sharp leading edges and with a body attached, over a range of Reynolds number from 1×10^6 to 12×10^6 and at incidences up to 42°. Photographs of the traces of an oil/titanium oxide mixture, on the surface, indicating flow directions, are included.—(1.10.2.2).

A technique for improving the predictions of linearised theory on the drag of straight-edged wings. D. G. Randall. C.P. 394. 1958.—(1.10.1.2).

Idealized wings and wing-bodies at a Mach number of 3. *E. D. Katzen. N.A.C.A. T.N.* 4361. *July* 1958.
Calculations indicate the possibility of obtaining high lift-drag ratios at a Mach number of 3, and some experiments which were designed to exploit the theory are described.—(1.10.2.2).

HELICOPTER AERODYNAMICS

Wind-tunnel investigation of effects of spoiler location, spoiler size, and fuselage nose shape on directional characteristics of a model of a tandem-rotor helicopter fuselage. J. L. Williams. N.A.C.A. T.N. 4305. *July* 1958.—(1.11.2).

Low tip Mach number stall characteristics and high tip Mach number compressibility effects on a helicopter rotor having an N.A.C.A. 0009 *tip airfoil section. R. D. Powell and P. J. Carpenter. N.A.C.A. T.N.* 4355. *July* 1958.
An investigation has been conducted on the Langley helicopter test tower to determine experimentally the low tip Mach number maximum mean lift coefficient and high tip Mach number compressibility effects on a helicopter rotor having a N.A.C.A. 0009 aerofoil tip section, a N.A.C.A. 0017 aerofoil root section, and 5·4° of negative twist. Data, presented for blade-tip Mach numbers ranging from 0·28 to 0.72 (corresponding blade-tip Reynolds number range of $1{\cdot}65 \times 10^6$ to $4{\cdot}29 \times 10^6$), have been compared with two-dimensional data as well as with other rotor experimental data.—(1.11.3).

TESTING AND INSTRUMENTS—*see also* STABILITY AND CONTROL

The influence of a model on plenum chamber indication of Mach number in a slotted wall wind tunnel. L. C. Squire and A. Stanbrook. C.P 395. 1958.
In many transonic tunnels the Mach number in the working section is determined from a pressure measured in the plenum chamber, on the assumption that this pressure is uniquely related to the free stream static pressure. The effect of a number of different sting-mounted models of solid blockage up to about ½ per cent on this relationship has been investigated in the 3 ft. tunnel at R.A.E. Bedford.—(1.12.1.2).

Some results of an investigation into the use of air injection in a model of the diffuser for the A.R.A. supersonic tunnel. E. C. Carter and K. F. Tucker. C.P. No. 386. 1958.—(1.12.1.2).

Investigation into the use of Freon 12 *as a working medium in a high-speed wind-tunnel. O. M. Pozniak. C.o.A. Note No.* 72. *November* 1957.—(1.12.1.2).

Summary of methods of measuring angle of attack on aircraft. W. Gracey. N.A.C.A. T.N. 4351. *August* 1958.
Wind tunnel calibrations of three types of angle-of-attack sensing devices: the pivoted vane, the differential pressure tube and the null-seeking pressure tube, are presented. Flight data on the position errors of three sensor locations, ahead of the fuselage nose, ahead of the wing tip, and on the forebody of the fuselage, are also presented. Various methods for calibrating angle-of-attack installations in flight are briefly described.—(1.12.2).

Development of the spark-heated, hypervelocity, blowdown tunnel-Hotshot. R. W. Perry and W. N. MacDermott. A.S.T.I.A. A.D. 157138. *June* 1958.
The history, description, performance, and typical test data for the first Hotshot type wind tunnel are presented. A brief account of advanced developments based on the electric-discharge method of heating gases is given. A family of instrumentation techniques has been developed which permits conventional pressure, heat transfer, and force tests to be made in the tunnel. Development type tests of components of a number of missiles have been conducted in the Mach number range of 11 to 20 and at equivalent density altitudes of 140,000 ft. to 200,000 ft.—(1.12.1.3).

Preliminary planning for a hypervelocity aeroballistic range at A.E.D.C. E. J. Stollenwerk and R. W. Perry. A.S.T.I.A. A.D. 157144. *June* 1958.
Results of preliminary experiments aimed at defining the design of a hypervelocity aero-ballistic range for the A.E.D.C. are reported and future possibilities discussed. An oscillator capable of withstanding a 200,000*g* acceleration has been developed. Scale-up of a hypervelocity gun using spark-heated hydrogen or helium as the propellant is also in progress.—(1.12.1.3).

A wide range hot-wire amplifier. H. M. Nelson and D. C. Collis. A.R.L. Report 1. 20. *January* 1958.
An amplifier is described which is to be used for the amplification of signals from a hot wire probe in an air stream containing velocity fluctuation components from a few c./sec. to 80 Kc./sec. Facilities are provided for the introduction of sharp cut-off low-pass filters in the output signal and for the differentiation of this signal when required.—(1.12.6.3).

Exploratory studies of hypersonic fluid mechanics. S. M. Bogdonoff. AGARD Report 142. *July* 1957.
Using a helium hypersonic wind tunnel, exploratory studies have been made of the flow over simple two- and three-dimensional bodies at Mach numbers from 11 to 19. Detailed studies of the flow over a flat plate are reviewed and preliminary results are presented for other configurations, including flat plates with flaps, delta wings, base pressure models, blunt models (with and without spikes) and slim cones. Some preliminary results of boundary layer studies and dissolving models are also discussed.—(1.12.1.3).

AEROELASTICITY

Supersonic wind tunnel flutter tests of two rectangular wings. P. R. Guyett. R. & M. 3080. 1958.
Two rectangular wings of aspect ratio 4 were flutter tested in a supersonic wind tunnel at Mach numbers 1·6 and 2·0 using a technique in which a structural stiffness was varied to give flutter at the Mach number. The results are in reasonable agreement with calculations. It is shown theoretically that structural damping has an important effect upon the stiffness required to avoid flutter, and may in some circumstances be destabilising.—(2).

Wind-tunnel tests on the effects of body freedoms on the flutter of a model wing carrying a localised mass. D. R. Gaukroger and E. W. Chapple. R & M. 3081. 1958.
Wind-tunnel test results for the flutter of a swept-back wing carrying a localised mass, and having symmetric or anti-symmetric freedoms of the root, are given. The chordwise and spanwise positions of a localised mass were varied for two localised mass values. In most of the symmetric flutter tests the inertia conditions of the fuselage were constant, and representative of full scale. For the antisymmetric tests, the fuselage rolling moment of inertia was varied.—(2).

Effect of boundary layer thickness on flutter of control surfaces. A brief survey of relevant reports. N. C. Lambourne. AGARD Report 183. *March-April* 1958.
Reports which contain information relevant to an assessment of the influence of the boundary layer on the flutter of control surfaces are listed.—(2 × 1.6.3 × 1.3).

AIRCRAFT OPERATION

See also AERODYNAMICS—LOADS

Turbojet engine noise reduction with mixing nozzle-ejector combinations. W. D. Coles et al. *N.A.C.A. T.N.* 4317. *August* 1958.
Several combinations of ejectors and nozzles were used and acoustic and engine performance data are presented.—(5.6).

EXTRA-ATMOSPHERIC TECHNOLOGY

On two parameters used in the physical theory of meteors. L. G. Jacchia. Smithsonian Cons. Aerophysics. Vol. 2, *No.* 9. 1958.
Observational results are given for two useful meteor parameters. The first is the "fragmentation index" which measures the progressive departure of the observed deceleration of a fragmenting meteor body from the deceleration expected on the basis of single-body theory. The second parameter is the coefficient σ of the "mass equation" $\dot{m}/m = \sigma v\dot{v}$.—(8.1).

Granulation and oscillations of the solar atmosphere. C. Whitney. Smithsonian Cons. Aerophysics. Vol. 2, *No.* 12. 1958.
The observations of solar granulation are briefly summarised and their interpretation is discussed. Steady-state solutions of the linearised equations of motion in two dimensions, subject to the boundary condition of an oscillating corrugation at the bottom of the solar atmosphere, are obtained and their observable properties outlined.—(8.1).

The statistics of meteors in the earth's atmosphere. G. S. Hawkins and R. B. Southworth. Smithsonian Cons. Astrophysics. Vol. 2, *No.* 11. 1958.
A random sample of 360 of the meteors doubly photographed by the Baker Super-Schmidt cameras has been taken. These meteors are fainter than those previously reduced. Their heights, velocities, radiants, and magnitudes have been accurately computed and are tabulated. Current meteor theory is briefly outlined, and certain of its predictions compared with statistics of the observed sample of meteors.—(8.1).

FLIGHT TESTING

Measuring in-flight thrust of a turbojet-powered aircraft. W. J. Coleman and D. F. DeSanto. AGARD Report 197. *April* 1958.
The theoretical formulation of a practical method for satisfactorily measuring the in-flight net thrust of a turbo-jet powered aircraft is described. Basic principles of thrust determination, current definitions and instrumentation techniques, including details of a traversing tailpipe rake are discussed.—(13.3 × 27.1.2).

HYDRODYNAMICS

Hydrodynamic impact loads of a −20° dead-rise inverted-V model and comparisons with loads of a flat-bottom model. P. M. Edge. N.A.C.A. T.N. 4339. *August* 1958.
Hydrodynamic impact loads data were obtained from tests of a narrow-beam model. Fixed-trim impacts were made in smooth water over a range of landing conditions. Loads, moments, motions, and bottom pressures were measured throughout each of the impacts. The maximum impact loads for the inverted-V model and flat-bottom model are compared.—(17.2)

MATERIALS

Transgranular and intergranular fracture of ingot iron during creep. L. A. Shepard and W. H. Giedt. N.A.C.A. T.N. 4285. *August* 1958.
Creep tests were performed on ingot iron at temperatures from 700° to 1,350°F to find whether the amount of grain-boundary sliding determined the fracture mode (transgranular or intergranular).—(21.2.1).

Influence of heat treatment on microstructure and high-temperature properties of a nickel-base precipitation-hardening alloy. R. F. Decker et al. *N.A.C.A. T.N.* 4329. *July* 1958.
Studies were made of the influence of various heat treatments on the rupture properties and microstructure of a 55Ni-20Cr-15Co-4Mo-3Ti-3Al alloy to provide more fundamental information on the relationships between structure and high-temperature properties in alloys of this type.—(21.2).

Effect of temperature on dynamic modulus of elasticity of some structural alloys. L. F. Vosteen. N.A.C.A. T.N. 4348. *August* 1958.
The effect of temperature on Young's modulus of elasticity was determined from flexural beam vibration tests for a range of alloys at temperatures up to 900°F. The test frequencies were varied from 40 to 550 cycles per second. The results are compared with values of moduli obtained from conventional stress-strain tests.—(21.2).

Elastomers for high temperature applications. E. R. Bartholomew. AGARD Report 178. *March-April* 1958.
The subject of Elastomer Technology is discussed. The source and nature of high-temperature elastomer problems are reviewed, and the limitations of the more conventional elastomer materials are discussed. Recent data on properties of special high-temperature polymers and their compounds are included.—(21.3).

Application of structural adhesives in air vehicles. D. L. Grimes. AGARD Report 181. *March-April* 1958.
The use of adhesives as structural joint media, for both aircraft and missiles, is dealt with. A systematic and detailed discussion is presented of the advantages and disadvantages of adhesives.—(21.3).

MATHEMATICS

Complex variable applications to certain coupled systems. D. P. Jenkins. C.P. 393. 1958.
It is shown that the solutions of similar differential equations which are coupled together can be expressed in terms of the solutions of a single differential equation, possibly containing complex parameters, but of the same order as each separate equation. Some implications are discussed, and Nyquist's criterion is generalised to study the stability of constant parameter systems of this type.—(22).

Sur quelques nouvelles généralisations de la théorie des nombres complexes et leurs applications. D. P. Riabouchinsky. Pubs Sc. et Tech. 343. 1958. *(In French).*
Some new generalisations on the theory of complex numbers and their application to subsonic, sonic, and supersonic flow of a compressible fluid and to turbulent flow of an incompressible fluid about a solid object are presented.—(22 × 1.2 × 1.4.2).

METEOROLOGY

Icing frequencies experienced during climb and descent by fighter-interceptor aircraft. P. J. Perkins. N.A.C.A. T.N. 4314. *July* 1958.
Relative frequencies of occurrence and severity of icing cloud layers encountered up to an altitude of 30,000 ft. are presented. Probabilities of icing severity (including average liquid-water content and maximum ice accretion) were calculated using earlier data measured in icing clouds.—(24).

POWER PLANTS

See FLIGHT TESTING

MISSILES

See AERODYNAMICS—LOADS

FATIGUE

See also AERODYNAMICS—FLUID DYNAMICS

Fatigue of structural materials at high temperatures. B. J. Lazan. AGARD Report 156. *November* 1957.
The general nature of the fatigue process is reviewed. The factors important in high temperature fatigue are tabulated. The nature and significance of creep phenomena which occur under various combinations of cyclic stress and mean stress are discussed. Resonant vibrations as a cause for fatigue are discussed. The roles of damping, elasticity, and conventional fatigue properties are analysed to provide criteria for judging resonance fatigue strength.—(31.2.2).